

THE EFFECT OF RESTORATION ON CO₂ EXCHANGE IN A CUTOVER
PEATLAND

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By

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ABSTRACT

Natural peatlands are important components in the global carbon cycle as they represent a net long-term sink of atmospheric carbon dioxide (CO₂), however, peatland extraction converts these ecosystems to persistent sources of atmospheric CO₂ following abandonment. Peatland restoration techniques have been developed with the aim to restore cutover peatlands to carbon-accumulating ecosystem. This is accomplished by raising the water table and reintroducing *Sphagnum* peat-forming species. The goal of this thesis was to examine effect of restoration on peatland-atmosphere CO₂ exchange at a cutover peatland.

Peat respiration decreased in the restored site post-restoration, which was partially due to the rewetting. However, the seasonal average peat respiration from both the restored and cutover sites were not significantly different from each other. Subsequently, rates of gross ecosystem production have increased over the same period due to the emerging vegetative cover, with seasonal mean net ecosystem exchange fluxes for both herbaceous and moss vegetation displaying significant improved net CO₂ fixation with time post restoration. Light response curves showing the relationship between gross ecosystem production of CO₂ (GEP) and photosynthetically active radiation (PAR) indicate that both the apparent quantum efficiency and the maximum GEP (A_{\max}) increased with time post-restoration.

Chamber flux measurements upscaled to the ecosystem level based on the percent cover of each plant species, indicate that the restored site, both one and two years post-restoration (2000, 2001) was a net sink of CO₂ over the study season (May-October), storing ~13.5 and 20.2 g C m⁻² respectively. Over the same study seasons, the cutover site remained a large source of CO₂, releasing ~136.8 and 83.0 g C m⁻² in 2000 and 2001 respectively.

Biomass measurements suggest that the restored site is storing substantial amounts of carbon in above and belowground biomass five years post-restoration. Total biomass estimates at the restored site ranged from 2227.23 g m⁻² for *Carex canescense* to 489.32 g m⁻² for *Polytrichum strictum*, corresponding to a mean annual NPP of 222.72 g C m⁻² and 48.99 g C m⁻² respectively.

Results of this thesis suggest that active ecosystem scale restoration techniques have the potential to return cutover peatlands to a net sink of atmospheric CO₂ within three to five years. The resultant increased storage of CO₂ post-restoration can be attributed in part by a reduction in peat respiration via active rewetting, in addition to the significant increase in ecosystem productivity from an evolving vegetative cover.

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CHAPTER 1: INTRODUCTION

1.1 Introduction

About 14% or 127.2 million ha of Canada, is covered by wetlands (Zoltai, 1988). Peatlands represent a large proportion of wetlands in Canada and cover an estimated 111.3 million ha (Zoltai, 1988). Natural peatlands are important components in the global carbon cycle (Gorham, 1991), storing ~33 % of the global soil carbon. These ecosystems represent a net long-term sink ($23\text{-}28 \text{ g C m}^{-2} \text{ y}^{-1}$) of atmospheric carbon dioxide (CO_2) (Gorham, 1991), however, climate and land-use change namely, peatland drainage and peat extraction are impacting this important biogeochemical function in peatlands. For example, extracted peatlands become persistent sources of atmospheric carbon dioxide (CO_2) following abandonment (Petroni et al., 2003; Waddington et al., 2002). However, there is plot scale evidence that peatland restoration is able to return an extracted peatland to a carbon-accumulating ecosystem (Waddington and Warner, 2001). If this process is able to occur at the ecosystem scale then it is possible to minimize the impact of peatland drainage and extraction. The aim of this thesis is to determine the change in CO_2 exchange following peatland restoration and to examine the ecohydrological processes controlling this exchange. With reference to restored peatlands, it is essential to assess when these sites will be fully “restored” from a carbon balance perspective. As such, this research will ultimately provide the knowledge necessary towards modelling the carbon balance of restored peatlands.

1.2 Peatland Ecosystems

Wetlands are dynamic ecosystems; at the transition zone between terrestrial and aquatic ecosystems (Mitsch & Gosselink, 1993). In Canada, a wetland is defined as “land that has the water table at, near or above the land surface, or which is saturated for long enough periods to promote wetland or aquatic processes as indicated by hydric soils, hydrophytic vegetation, and various kinds of biological activity that are adapted to the wet environment” (Tarnocai, 1988). The Canadian Wetlands Classification System (CWCS) defines five classes of wetlands by their individual chemical, biotic and hydrological gradients. They are: swamps, fens, marshes, shallow open water, and bogs (National Wetlands Working Group, 1988). Peatlands are classified as “wetlands with a peat depth of 40 cm or greater” (Zoltai, 1988), and include bogs, fens and some swamps (Tarnocai, 1988). Fens by definition have nutrient rich conditions, distinguished by a high water table and very low seepage (Zoltai, 1988). Sedges, reeds, grasses and mosses are the characteristic vegetation of these fen ecosystems. Bogs are defined as “rain-fed” or ombrotrophic ecosystems that are nutrient-poor, generally have high water tables and their surface is covered with *Sphagnum* mosses and ericaceous shrubs (Tarnocai, 1988). Furthermore, swamps tend to be treed wetlands and have seasonally standing or slow moving water (Zoltai, 1988).

1.3 Peatland Carbon Cycling

1.3.1 Carbon Balance

Carbon accumulates in peatlands because of the slow rate of peat decomposition in anaerobic waterlogged conditions. The process of peat formation generally creates two distinct layers, the acrotelm and the catotelm (Ingram, 1979). The upper (10-50 cm) aerobic layer or acrotelm, has a high decay rate, porosity and hydraulic conductivity; however, it is poorly decomposed (Clymo, 1984). The thicker catotelm, which lies beneath the acrotelm has a higher bulk density with subsequent low porosity and hydraulic conductivity. Furthermore, the catotelm exhibits a slow decay rate, due to its anaerobic conditions (Clymo, 1984).

Peatlands store more soil carbon than any other ecosystem, containing up to one third of the world's soil carbon pool with an estimated long term storage of $\sim 23 \text{ g C m}^{-2} \text{ y}^{-1}$ (Gorham, 1991). The storage of carbon is determined by the balance between primary production (photosynthesis) and decomposition (Clymo, 1984).

The contemporary carbon balance can be represented by:

$$\Delta C = \text{CO}_2(\text{GEP}) - \text{CO}_2(\text{RTOT}) - \text{CH}_4 - \text{DOC} \quad [1]$$

In most cases, the carbon balance of peatlands is dominated by CO_2 cycling, representing up to 90% of the carbon exchange (Gorham, 1995), under both aerobic and anaerobic conditions. As such, the cycling of CO_2 is frequently used as a measure of peatland carbon storage (Gorham, 1991). Carbon dioxide (CO_2) is fixed by plants in process of photosynthesis (GEP) to form organic carbon, and O_2 (Schlesinger, 1997). CO_2 is removed from the ecosystem by the decomposition of organic matter. Total

ecosystem respiration (R_{TOT}) includes soil, plant and root respiration and is dependent on the amount of labile material, soil temperature, and soil moisture content (Waddington et al., 2002). Thus, the total net ecosystem exchange (NEE) is a measure of the difference between CO_2 uptake by photosynthesis (GEP) and total respiration (R_{TOT}). Depending on the type of peatland and the conditions present, daily NEE can range from between -5 to 3 g C m^{-2} (Gorham, 1991).

The other components of the carbon balance include methane (CH_4) and dissolved organic carbon (DOC). CH_4 is produced under waterlogged, anaerobic conditions, by the process of methanogenesis. Natural peatlands emit $\sim 4.0 \text{ g C m}^{-2} \text{ yr}^{-1}$ (Gorham, 1991) of atmospheric CH_4 worldwide, accounting for $\sim 15\text{-}30\%$ of the total atmospheric burden of CH_4 . In addition, peatlands can provide a large input of dissolved organic carbon (DOC) to downstream aquatic ecosystems (Gorham, 1991). DOC is comprised of both fulvic and humic acids, and can often exceed concentrations of 50 mg L^{-1} in peatland soils (Dalva & Moore, 1991). While DOC and CH_4 are important, this thesis will specifically focus on the major component of the peatland carbon cycle, namely the exchange of CO_2 .

1.3.2 Controls on CO_2 Exchange

1.3.2.1 Peat Respiration

CO_2 production by the process of respiration is dependent on a number of environmental parameters including soil temperature, soil moisture content and substrate quality (Moore and Dalva, 1993). Warmer soil temperatures enhance the rate of microbial reactions (Updegraff et al., 1998), including an increased rate of CO_2 production (McKenzie et al., 1998). The rates of microbial processes, including respiration typically

double for every 10°C increase in temperature, up to an optimum of 35 - 40°C (Bridgham et al., 1998).

The position of the water table and capillary fringe generally determines the oxic-anoxic ratio within the peat profile (Waddington and Price, 2000). Lowering the water table enhances organic matter decomposition owing to an increase in the depth of the aerobic zone. Similarly, soil moisture also plays a fundamental role in soil respiration, as drought stress and reduced CO₂ emission can occur as water becomes limiting for microbial activity (Lomander et al., 1998; Subke et al., 2003). However, waterlogged or anaerobic conditions tend to exhibit slow rates of decomposition by limiting the availability of O₂, as the rate of diffusion of gasses in water is ~10, 00 times slower than in air (Jackson, 1985). This ultimately reduces the rate of aerobic microbial activity, leading to organic matter accumulation (Clymo, 1984).

Substrate quality, specifically, the amount of labile organic matter also plays a pivotal role in the rate of organic matter decomposition in soils. Labile carbon pools are easily decomposable substrates in plant residues, including: simple sugars, starches and cellulose. In contrast, recalcitrant compounds, including lignins, are complex compounds that are resistant to decomposition and thus have slow rates of decay (Bridgham et al., 1998). *Sphagnum* in particular exhibits very slow decomposition rates due to their recalcitrant chemical composition. Interestingly, Scanlon and Moore (2000) found that the degree of decomposition (von Post index), an indication of substrate quality, was most strongly correlated with CO₂ production, as compared with temperature and soil moisture.

Substrate nutrient concentrations, specifically, C:N ratios of organic matter are an additional control on CO₂ efflux (Moore et al., 2004) as it gives an indication of the potential rate of decomposition of a substrate. It is suggested that nitrogen concentrations tend to limit the decomposition of organic matter as soil microbes require a balance of nutrients for growth and maintenance (Brady and Weil, 1999). Soil nutrient availability is low in bogs due to the lack of nutrient rich groundwater inputs (Bridgham et al., 1998; Hornibrook et al., 2000) and by a reduction in mineralization under anaerobic conditions. Therefore, nutrient availability is heavily dependent on internal cycling in these ecosystems. Previous studies have found that bogs have fairly high C:N ratios. For example, Hornibrook et al., (2000) found that litter from characteristic bog species, including *Sphagnum* had C:N ratios greater than 50. Similarly, a study conducted by Francez et al., (2000), at a restored peatland in France found that peat C:N ratios varied depending on depth of peat; and values ranged from 36 in the surface peat to a low of 16 at 160 cm depth. However, it is suggested that low nutrient concentrations are not as important controllers of respiration as compared to substrate quality (Bridgham and Richardson, 1992).

The effects of temperature and soil moisture on plant and soil respiration is confounded by the evolution of a vegetative surface cover in restored peatlands (Petroni et al., 2003). In fact, research has shown that there is strong correlation between primary productivity and respiration (Bubier et al., 1998; Xu and Qi, 2001). For example, Raich and Tufekcioglu (2000) propose that vegetation may affect soil respiration by influencing the microclimate of the soil, the quality and quantity of detritus added to the soil, and by

providing additional respiration from their roots. Raich and Schlesinger (1992) found a significant relationship ($r^2 = 0.87$) between net primary productivity and soil respiration. In fact, studies have also found a correlation between aboveground biomass and respiration (Bubier et al., 2003a), reinforcing the idea that the larger the plant, the greater the potential supply of detritus to the soil, which provides microbes with a fresh labile carbon source. In addition, vegetation may also create a “priming effect” whereby root exudates can be used as an energy source for soil microorganisms and as a result increase the microbial activity in this portion of the soil. (Kuzyakov et al., 2000 and 2001). According to Gaillard et al. (1999), fresh organic residues can be viewed as “temporal hot spots” of microbial activity. It is estimated that ~35-45% of total respiration can be attributed to respiration from below ground biomass (Silvola et al., 1996).

1.3.2.2 Gross Ecosystem Production

The dominant environmental control on gross ecosystem production (GEP) is photosynthetically active radiation (PAR) (Bubier et al., 1998). Seasonal production is often modelled as a rectangular hyperbolic relationship between GEP and PAR (Frolking et al., 1998) (light response curves). However, this relationship can be complicated by a number of factors including: vegetation temperature, soil and vegetation potential, atmospheric moisture deficit, internal and ambient CO₂ concentrations and nutrient status.

As with respiration, water availability is also crucial for carbon assimilation (Schipperges and Rydin, 1998), especially for *Sphagnum* moss species due to their limited capability to control water loss (Titus & Wagner, 1984). *Sphagnum* mosses are

non-vascular plants and use capillary action to replace water lost by evaporation (Hayward and Clymo, 1982). Previous studies suggest that *Sphagnum* colonization increases with a reduction in soil tension and increased water levels (Price et al., 1998). Water availability, specifically the moisture content of the *Sphagnum* moss carpet is suggested to be the most important factor controlling growth (Buttler et al., 1998) compared to both temperature and PAR. Furthermore, studies have shown growth and productivity of *Sphagnum* in natural peatlands is maximized with increased water levels (Hayward & Clymo 1982; McNeil and Waddington, 2003) and increased *Sphagnum* moisture content (Schipperges & Rydin, 1998). A greenhouse experiment conducted by Williams et al. (1999) concluded that *Sphagnum* productivity significantly decreased with a lowering of the water table by 30 cm. Similarly, Schipperges & Rydin, (1998) examined the resiliency of mosses to recovery from desiccation and found that *Sphagnum* mosses did not recover from complete desiccation. Specific limits of *Sphagnum* growth have been determined from previous studies that suggest *Sphagnum* mosses can no longer generate suction to hold water in their hyaline cells where soil water tension is less than –100 mb (Hayward and Clymo, 1982), ultimately leading to desiccation. As well, Schouwennars (1988), suggests that a mean water table position exceeding 40 cm below the surface is detrimental to the recolonization of *Sphagnum*. However, a more recent study conducted by Price (1996) suggests that water in the unsaturated zone is more important to *Sphagnum* survival than the level of water table to support tensions less than –100 mb.

In addition, primary productivity in ombrotrophic peatlands is often limited by soil nutrient availability (Chapin et al., 2004), specifically P, N and sometimes K. Consequently, bog species, namely *Sphagnum* mosses are adapted for these poor nutrient conditions, through their characteristic slow growth rates and increased root to shoot ratios (Bridgham et al., 1998). *Sphagnum* spp. also have the ability to acidify their surroundings and thus, can out compete any other species present (van Breeman, 1995) by having a high nutrient retention capacity and by creating harsh conditions. In contrast, *Sphagnum* mosses cannot survive under conditions of low water table or high soil tension (Hayward and Clymo, 1982).

1.4 Peatland Extraction

Over the past century many peatlands have been drained and extracted for horticultural, energy or agricultural purposes (Rochefort, 2000). As a result of the large demand for horticultural peat in Canada, over 12 000 ha of peatlands are cutover (Cleary, 2003). In some regions of Canada such as the St. Lawrence lowlands of Québec, peatland losses are extensive and exceed 70% (Van Seters and Price, 2001). In North America, the vacuum extraction technique is currently the most popular method (Petroni et al., 2001) for the horticultural industry. The first step in preparing a peatland for extraction is the drainage of the peatland (Rochefort et al., 2003). Peatland drainage enhances organic matter decomposition due to an increase in the depth of the oxic zone. This step is then followed by the removal of the surface vegetation, including *Sphagnum* mosses, and the acrotelm (Petroni et al., 2001; Waddington & Price, 2000) to a depth of ~75 to 100 cm.

Therefore, in peat extraction the viable seed bank (Lavoie and Rochefort, 1996; Petrone et al., 2001) and a labile carbon source in the upper peat layers have been removed (Waddington et al., 2002). As a result, deeper, more decomposed catotelmic peat is exposed at the surface, which has different chemical and structural properties compared to acrotelmic peat (Wind-Mulder et al., 1996). In addition, the higher bulk density and reduced porosity of this peat results in a decreased hydraulic conductivity and a lower specific yield (Price et al., 2003). In addition, 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) as a result of reduced buoyancy. Subsidence further decreases peat pore sizes (Price, 2003), which ultimately affects *Sphagnum* growth as it obtains water via capillary action.

1.4.1 Impacts on Carbon Cycling

Peatland drainage and extraction subsequently reduce the flux of methane (CH₄) emissions and in turn, increases CO₂ emissions to the atmosphere by a decrease in water table creating an increase in aerobic decomposition and CH₄ oxidation, in addition to the removal of carbon fixing vegetation (Waddington and Price, 2000). According to Silvola et al. (1996), drainage caused a 100% increase in CO₂ fluxes compared to natural sites. After approximately 20-50 years of peat extraction the site is abandoned (Tuittila et al., 1999), and the bare peat surface is often left to regenerate on its own devices. In most cases the physical and hydrological conditions that are necessary for *Sphagnum* moss re-establishment and carbon sequestration have been eliminated (Price, 1997). Hence, GEP remains close to zero many years after extraction has ceased. As a result, extracted

peatlands become persistent sources of atmospheric carbon dioxide (CO₂) (Petrone et al., 2003; Waddington and Warner, 2001). In fact, research conducted by Waddington et al., (2002) determined that a site released 363 g CO₂-C m⁻², 2 years after abandonment compared to 399 g CO₂-C m⁻² released from a site abandoned for 7 years. Waddington and McNeil (2002) found that peat oxidation rates remained high even after two decades of post extraction abandonment. In contrast, other studies have found that peat extraction decreased total bacterial and microbial biomass (Croft et al., 2001), which ultimately reduces the CO₂ production potential at these sites.

1.5 Peatland Restoration

Extracted cutover peatlands rarely return to functional peatland ecosystems after abandonment. In most cases the physical and hydrological conditions that are necessary for *Sphagnum* moss re-establishment and carbon sequestration have been eliminated (Price, 1997; Van Seters & Price, 2001). These extracted peatlands are drier compared to natural peatlands due to the removal of water by drainage ditches, and the large loss of soil moisture due to enhanced evapotranspiration (Price et al., 1998; Van Seters & Price, 2001). Peat exposed at the surface for a long time after abandonment, results in increased decomposition and changes in peat properties. Consequently, Gorham and Rochefort (2003) stress the importance of conducting peatland restoration immediately after extraction has commenced in order to further reduce degradation and return the natural carbon sink function of these impacted peatland ecosystems. Currently, approximately 300 ha of peatlands are undergoing restoration in Canada (Cleary, 2003).

In order to promote *Sphagnum* moss, which obtains its water by capillary action (Price, 1997) to re-colonize, normal peatland hydrologic and biogeochemical functions must be re-established (Gorham and Rochefort, 2003). The North American approach to peatland restoration as explained in Rochefort et al. (2003), includes: field preparation, *Sphagnum* diaspore collection and introduction, straw mulch application to provide diaspore protection and in some cases fertilization to return cutover areas to functioning peatland ecosystems. Field preparation is conducted in order to provide suitable hydrological conditions for moss re-establishment; this is carried out by the blockage of drainage ditches to rewet the surface (Quinty & Rochefort, 1997), the creation of dykes and sometimes the construction of open water ponds (Quinty & Rochefort, 1997). Secondly, *Sphagnum* diaspores are introduced to the site from a natural donor peatland in either a 1:10 or 1:15 ratio in order to minimize the impact on natural bogs and to insure rapid plant establishment (Rochefort et al., 2003). These diaspores are protected by a straw mulch applied at a rate of 3 000 kg ha⁻¹ which provides improved microclimatic conditions, specifically, reducing tension in the surface layer and increasing soil moisture (Price et al., 1998). For example, Price et al., (1998) found that water table levels were higher under straw mulch compared to sites with only bare peat, where 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. Lastly, in some cases, phosphorus fertilizer is applied to enhance rapid colonization by vascular plants, which act as nursing plants to *Sphagnum* mosses (Rochefort et al., 2003). As a result, peatland restoration has the opportunity to

return the peatland to a carbon accumulating system (Waddington & Price, 2000) and maybe even to a net carbon sink (Tuittila et al., 1999).

1.5.1 Impacts on Carbon Cycling

Most studies conducted in restored peatlands have shown a decreased release of CO₂ to the atmosphere with active rewetting, due to a reduction in aerobic decomposition (Waddington and Warner, 2001). A plot scale study conducted by Waddington and Warner (2001), concluded that the restored plot showed more than a two times reduction in the CO₂ equivalents released to the atmosphere compared to the abandoned peatlands. It was estimated that 70% of this decrease in CO₂ emissions post restoration was due to an increase in GEP and 30% was due to a decrease in soil respiration (Waddington and Warner, 2001). Unfortunately, this restored site had still not returned to the natural carbon sink due to high soil respiration values. European studies have also demonstrated a reduction in CO₂ efflux post-restoration. A study conducted by Tuittila et al. (1999), found that active rewetting decreased respiration as well as increasing productivity at the site, specifically from *Eriophorum* spp. Within two years post-restoration, the site became a net sink of atmospheric CO₂ from the dense *Eriophorum* cover. Similarly, Komulainen et al. (1999), found that rewetting drained peatlands increased *Eriophorum* cover and ultimately changed the seasonal carbon balance towards an increase in CO₂ sequestration.

In contrast, other studies have demonstrated that post-restoration; total respiration may increase due to the addition of labile organic matter from a newly established vegetative cover (Croft et al., 2001). In fact, recent research conducted using the eddy covariance

micrometeorological technique at a restored cutover peatland in eastern Québec (Bois-des-Bel), has shown a significant increase in carbon dioxide fluxes to the atmosphere three years post-restoration (Petrone et al., 2003). The net CO₂ source post restoration is approximately double the rates of CO₂ fluxes pre-restoration despite active restoration techniques (Petrone et al., 2001). The 2000 and 2001 NEE seasonal averages are 478.0 g C m⁻² and 468.1 g C m⁻² respectively. Approximately 20% of this increase is a result of decomposing straw mulch used in the restoration process (Waddington et al., 2003a), also due to the lack of a carbon fixing vegetative surface and variable moisture conditions.

1.6 Objectives

With reference to restored peatlands, it is essential to assess when these sites will be fully “restored” from a carbon balance perspective.

The specific objectives of this research, therefore are to:

- 1) Characterize spatial and temporal variability of net ecosystem exchange of CO₂ at a restored and cutover peatland one, two and three years post-restoration;
- 2) Determine dominant biogeochemical processes controlling CO₂ exchange;
- 3) Empirically model the seasonal CO₂ exchange at a restored and cutover peatland;
- 4) Determine the amount of carbon accumulation present in both above and belowground biomass five years post-restoration.

CHAPTER 2: STUDY AREA

2.1 Study Area

This study was undertaken at the Bois-des-Bel peatland located in the Bas-Saint-Laurent region of Québec, ~14 km east of Rivière-du-Loup (42°58' N, 69°25' W). The mean annual temperature for the region is 3°C, with mean January and July temperatures of -12 and 18°C, respectively. The mean annual precipitation is 926 mm with 27% falling as snow (Environment Canada, 1993). The Bois-des-Bel peatland is a ~200 ha treed bog of which an 11.5 ha section of the peatland drained in 1972 and subsequently vacuum extracted from 1973 to 1980 after which it was abandoned until 1999 (Figure 2.1). The abandoned peatland was divided into 11 fields (30 m x 300 m), and separated by drainage ditches running parallel (North-South) to the fields. In the autumn of 1999, ecosystem scale restoration commenced using the standard North American restoration techniques as outlined in Rochefort et al. (2003). Initially the surface was cleared of all vegetation and woody material that was present after abandonment. Drainage ditches were blocked and dykes (low-lying peat walls) were created to retain snowmelt. *Sphagnum* diaspores were also introduced from a natural donor peatland, after which they were protected by a straw mulch cover applied at a rate of 3 000 kg ha⁻¹. Lastly, phosphorus fertilizer was applied at a rate of 15 g m⁻² to enhance vascular plant colonization (Rochefort et al., 2003). The extracted peatland was separated into two catchments: a 7.5 ha restored section (westernmost peat fields 1-8) and a 1.8 ha cutover section (easternmost fields 10-11) with a buffer strip left in-between the two catchments (field 9). The restored section of the Bois-des-Bel peatland is further divided into four

zones (1-4) and separated by dykes. Zones 2, 3 and 4 were restored in the fall of 1999, while zone 1 was restored in the fall of 2000. The average peat depths of the restored and cutover sites are 1.5 and 1.6 m respectively (Day, 2003). The dominant species found at Bois-des-Bel post-restoration include: *Polytrichum* spp., *Ericaceous shrubs*, *Eriophorum vaginatum* and *Typha latifolia*. Furthermore, *Sphagnum* spp. was present at the restored site while *Picea mariana* and *Betula* spp., were present at the cutover site.

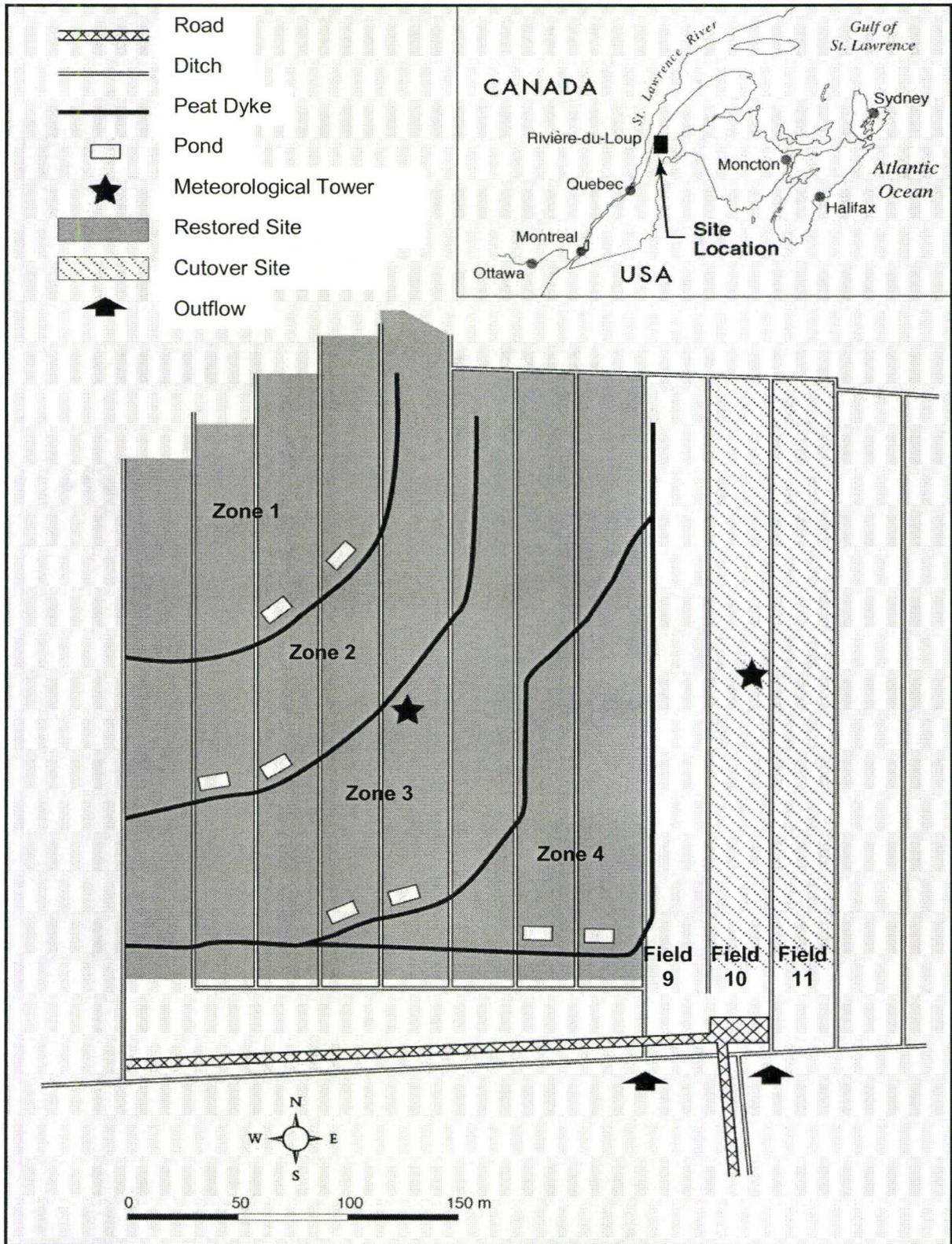


Figure 2.1: Site map of Bois-des-Bel peatland.

CHAPTER 3: METHODS

3.1 Methodology

3.1.1 *Field Methods*

Data was collected from mid May to early October in 1999, 2000, 2001 and 2002. In 2004, detailed experiments and biomass samples were conducted between mid July and mid August. Mean seasonal values were calculated from May 1st to August 31st to allow for interannual comparison.

3.1.1.1 *CO₂ Flux Measurements*

Net ecosystem exchange fluxes were sampled using the chamber technique several times a week over the four study seasons at multiple locations representing all the dominant vegetation surface coverages, including bare peat, ditches, moss species (*Sphagnum* and *Polytrichum*) and herbaceous species (*Eriophorum*) in both the cutover and restored sites. Permanent sampling locations were located off the major boardwalks at the site to minimize disturbance. Between three and thirteen replicates of each surface type were used to ensure representativeness of the flux measurements.

The chamber technique is described in detail in Griffis et al. (2000) and Waddington et al. (2002). Briefly, a cylindrical chamber of a known surface area (0.05 m²) and volume (20 L) is placed and sealed over PVC collars inserted into the peat to a depth of ~10-15 cm at each sampling location. A dark chamber was used to measure respiration and a clear Plexiglas chamber was used to measure net ecosystem exchange (NEE). Clear chambers were equipped with a cooling device to maintain ambient temperature

conditions (Griffis et al., 2000). To establish relationships with NEE and PAR, a series of shrouds of various mesh sizes were placed over the clear chamber to measure NEE under reduced light conditions. All chambers were equipped with a fan to ensure air is well mixed during the sampling period. The concentration of CO₂ in the chamber headspace was measured using an infrared gas analyzer (IRGA) (PP systems EGM-2) at one-minute intervals over a duration of 5 minutes. Final CO₂ flux measurements are calculated as a change in concentration over the 5-minute interval and were corrected for volume changes and temperature variations. In addition, gross ecosystem production (GEP) was determined as a residual by subtracting the NEE values by the respiration values obtained from the same collar in the same sampling period. CO₂ fluxes were reviewed for quality control purposes, fluxes calculated from the slope of the gas concentration verses time in chambers has R² values of 0.70 or less were deleted, except for the cases of zero flux.

To assess the spatial variability in CO₂ fluxes from both bare peat and ditch collar locations, two 30 m ditch to ditch transects were sampled during the 1999 study season at both the cutover and restored sites. The temporal variability of the CO₂ fluxes was assessed by capturing short-term responses of the site by conducting multiple diurnal flux measurements at a selection of collar locations during the 2004 study season. Specifically, NEE fluxes were sampled from a replicate of each surface coverage sampled during the 2004 study season at both the cutover and restored sites at three hour intervals over a duration of 24 hours. Previous research has shown that using daytime measurements of CO₂ flux only tends to overestimate daily mean flux by ~4-6% (Xu and Qi, 2001).

3.1.1.2 Environmental Variables

Two micrometeorological towers were located in both the restored and cutover sites (Figure 2.1) for the continuous measurement of precipitation, temperature, soil moisture, water table position as well as photosynthetically active radiation (PAR). Precipitation was measured every half-hour using a tipping bucket rain gauge (Campbell Scientific, Utah) connected to a CR 21x datalogger, as well as from two manual gauges. Air temperature was measured using a thermocouple and peat temperatures were obtained using a series of thermocouples installed in the peat at various depths (0, 2, 5, 10, 25, 50 and 75 cm). Soil moisture was measured with Campbell CS615 moisture probes at both 5 and 50 cm depths (Campbell Scientific, Utah) and water table levels were monitored hourly using remote data system (RDS) wells in addition to manual measurements. Finally, PAR was measured continuously using a LI-COR quantum light sensor (LI-COR Inc., Nebraska). All tower measurements were recorded using a CR 21x datalogger (Campbell Scientific, Utah) every ten seconds and were then averaged to give half-hourly values.

In addition, simultaneous measurements of air temperature, peat temperature, soil moisture and PAR were made during chamber CO₂ sampling. Air temperature (°C) and peat temperature (°C) at 2, 5 10 and 15-cm depths was recorded at each site during sampling using a Comark, KM43 temperature probe ($\pm 0.3^{\circ}\text{C}$). Volumetric moisture content (VMC%) for the upper 10 cm of the underlying peat was measured using a Campbell Scientific Hydrosense (CD620) Soil Moisture TDR Probe, with a probe length of 12 cm and a $\pm 3\%$ accuracy. When measuring NEE, PAR was also recorded (Li-COR

quantum light sensor, $\mu\text{mol m}^{-2} \text{s}^{-1}$). These instantaneous measurements of soil temperature, VMC and soil moisture were used to establish site and collar specific empirical relationships with CO_2 flux.

3.1.2 Laboratory Methods

3.1.2.1 Peat Properties

At the end of the 2004 study season, 8 x 8 x 5 cm soil cores were removed from below each collar location, at 0-5, 5-10 and 10-15 cm depths. Samples were frozen, returned to McMaster University until analysed. von Post degree of decomposition was determined for all cores by standard method (von Post, 1922). The peat samples were squeezed within a closed hand, and the colour of the solution that was expressed between the fingers, the nature of the fibres, and the proportion of the original sample that remained in the hand was observed. From these observations the soil sample was placed in one of ten classes (H1-H10).

Additionally, C:N ratios were determined from a sub sample of each core taken during the 2004 field season. Each peat sample was air dried and sent to University of Alberta for analysis. Whereby, peat cores were finely ground and weighed before samples were combusted in a COSTECH Elemental Analyzer (Italy), which employed the Dumas Combustion Technique. In the presence of oxygen, peat samples were then combusted at 1800°C, liberating all the gases that are reduced, dried and passed through a GC column for separation and detection with a TCD detector.

3.1.2.2 Aboveground Biomass

At the end of the 2004 field season, aboveground biomass samples were removed from each collar by clipping all above ground vegetation present to the discoloration of the *Sphagnum*. If there was no *Sphagnum* present biomass was cut to the discoloration line of the *Polytrichum* mosses. Samples were frozen pending analysis at Laval University. Procedures follow that of Bubier et al. (2003) and Moore et al. (2002); where material was sorted by species and into leaves and stems. Specifically for *Polytrichum* mosses; brown, red or yellow are considered green biomass. For herbaceous species, any leaves that were totally dead (denoted by dark colour) were placed in litter category. However, different conditions apply if only portions of the leaf were dead, specifically, if more than 50%, then the dead portion was removed and put it in the litter category, if less than 50% dead it would be included as green biomass. For vascular species, the whole leaf was kept in the green biomass category unless it was 100% dead. If there were any adventives roots present (often in collars with a lot of *Sphagnum*) on ericaceous plants, they were cut and placed in the below ground biomass division. Plant tissues were then dried at 60°C for 48 hours and then weighed.

3.1.2.3 Belowground Biomass

Belowground biomass samples were removed to a maximum depth of 25 cm below each collar sampled during the 2004 study season. Each sample was frozen pending analysis at McMaster University. Root biomass was conducted similarly to Moore et al. (2002). Cores were subdivided into 5 cm increments where belowground biomass was

then sorted from the peat into a coarse (> 2mm), medium (< 2mm and > 0.5 mm) or fine (< 0.5 mm) category. Root tissues were oven dried at 60°C for 48 hours and weighed.

3.1.3 Data Analysis

Regression analysis was conducted to determine the relationship between the measured environmental variables and peat properties to CO₂ flux. Secondly, ANOVA and t-tests were conducted among normally distributed permanent collar locations to determine significance between fluxes. In the case of non-normal distributed data, a Mann-Whitney non-parametric test was used to determine statistical significance. In order to interpret the spatial variation of CO₂ fluxes at the site, the mean, standard deviation and the coefficient of variation among all collar locations were calculated.

The response of photosynthesis was modelled based on light levels using a non-rectangular hyperbola relationship [2] from collected field data of PAR and GEP, where Φ , k and A_{\max} were determined using modelling software called Photosyn Assistant (Dundee Scientific).

$$A = \frac{\Phi Q + A_{\max} - \sqrt{((\Phi Q + A_{\max})^2 - 4\Phi Q k A_{\max})}}{2k} \quad [2]$$

Where A = net leaf photosynthesis

Q = PAR

Φ = apparent quantum efficiency (initial slope)

A_{\max} = maximum gross photosynthetic exchange of CO₂

k = convexity value

Chamber data was upscaled to the ecosystem level using the “measure and multiply” method [3] where fluxes were multiplied by the corresponding percent coverage of that element or vegetation class in the peatland.

$$F = \sum (A_i \times F_i) \quad [3]$$

Where F = Total flux

F_i = Flux from vegetation “i”

A_i = % cover of vegetation “i”

CHAPTER 4: ENVIRONMENTAL VARIABLES

4.1 Environmental Variables

In order to explain the interannual variability in CO₂ fluxes the changes in climatic and environmental conditions both pre (1999) and post-restoration (2000, 2001 and 2002) need to be characterized. Seasonal total precipitation (May 1 to August 31) was measured at the restored site pre and post restoration, however, no field data was collected in May of the 1999 season and thus, there is an incomplete data set for that year. However, when comparing the seasonal precipitation post-restoration (2000, 2001 and 2002), it is evident that the 2001 season had ~15 mm and ~33 mm more precipitation than the 2000 and 2002 field seasons respectively (Table 4.1).

Table 4.1: Interannual variability in total seasonal precipitation (1999, 2000, 2001 and 2002) compared to the 30 year mean.

Month	Precipitation (mm)				
	30 yr. mean	1999	2000	2001	2002
May	89.6	N/a	88.9	59.9	72.3
June	87.1	96.3	20.3	54.2	59.8
July	92.0	107.3	74.4	87.8	94.1
August	97.5	32.7	88.7	84.1	27.1
<i>Seasonal</i>	<i>366.2</i>	<i>236.3</i>	<i>272.3</i>	<i>286.0</i>	<i>253.3</i>

In all sampling years, both pre and post restoration, Bois-des-Bel experienced drier conditions compared to the 30-year mean total precipitation (Table 4.1). Most notably, during the 2002 study season, Bois-des-Bel experienced drought like conditions during

August, with only 27.1 mm of precipitation compared to the 30-year mean of 97.5 mm over the same time period.

The mean water table depth for both the restored and the cutover sites are quite similar pre-restoration (1999), which is to be expected as no active rewetting (restoration) had occurred. However, in 2000, one year post-restoration a large increase in the water table depth at the restored site was observed; where depth increased from -54.8 cm in 1999 to -31.5 cm in 2000, due to active rewetting, specifically the blocking of the drainage ditches. And in 2001, the restored site average water table depth was only slightly higher compared to the 2000 field season (-30.4 cm); which could be attributed to the greater field season precipitation compared to 2000. In contrast, during the dry 2002 study season, both the cutover and the restored site had an increase in the seasonal depth to water table. Each year post-restoration the restored site water table depth was significantly higher than the cutover site.

Table 4.2: Water table depths (cm) for the cutover and restored sites, pre (1999) and post-restoration (2000, 2001 and 2002).

		Water Table (cm)	
		Cutover	Restored
Pre-Restoration	1999	-51.4	-54.8
Post - Restoration	2000	-46.0	-31.5
	2001	-39.5	-30.4
	2002	-43.8	-35.9

Volumetric soil moisture values show that there is little seasonal variability in the mean soil moisture within both sites, however there are significant differences between the restored and cutover sites, specifically at 5 cm depth (Figure 4.1). The restored site

has much higher soil moisture values compared to the cutover site post-restoration. The average volumetric soil moisture values from the restored site meteorological tower were 62%, 49% and 38% for 2000, 2001 and 2002 study seasons respectively. With the 2000 study season being significantly wetter than both the 2001 and 2002 seasons. In contrast, the cutover site had significantly lower seasonal average volumetric soil moisture values of 34%, 20% and 39% for the 2000, 2001 and 2002 seasons compared to the restored site. Previous studies at the site have shown that average volumetric soil moisture measurements made from multiple locations in both the restored and cutover sites that for all three years post-restoration, the mean soil moisture values at a depth of 5 cm were greater than 50% over the whole study season (Shantz, 2003) at the restored site. However, the cutover site rarely had average seasonal soil moisture values over 50% (Shantz, 2003).

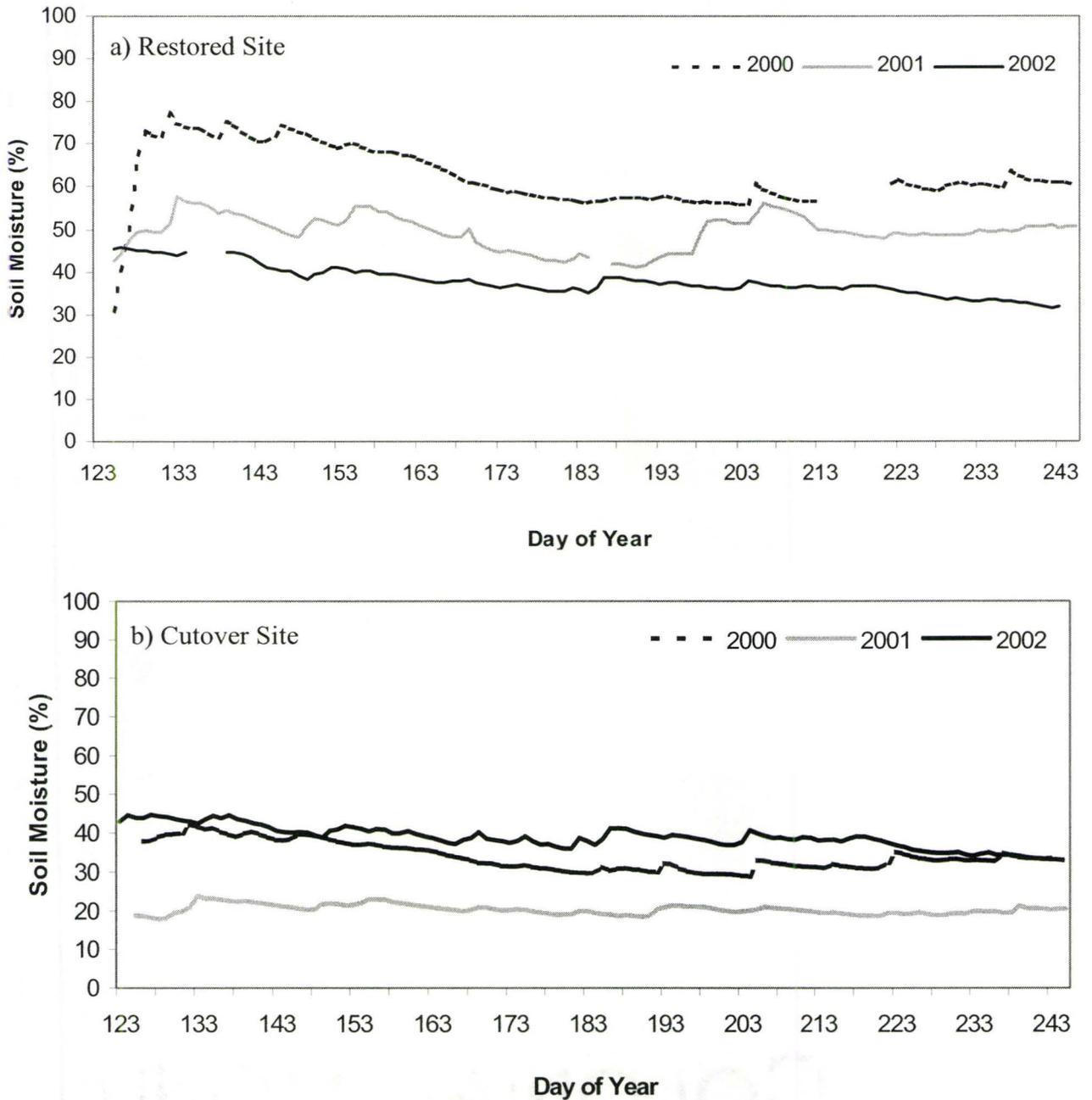


Figure 4.1: Interannual variability in volumetric soil moisture content at 5 cm depth for the a) restored and b) cutover sites.

Daily average air temperature at the restored site (Figure 4.2), both pre (1999) and post restoration (2000, 2001 and 2002) showed a general trend to increasing temperatures during mid summer. However, there was no significant difference in the seasonal mean average air temperature between the three field seasons. All three years were within two degrees of the 30 year summer mean (Day, 2003); where the seasonal mean average air temperatures for 1999, 2000, 2001 and 2002 were 16.2, 14.2, 15.8 and 16.5 °C respectively (Table 4.3).

In addition, interannual variability in peat temperature at 5 cm depth (Figure 4.3) measured at both restored and cutover micrometeorological towers. The restored site shows a general increase in peat temperature at 5 cm depth with time post restoration. Specifically, seasonal average peat temperature at the restored site was 13.8, 15.4 and 16.1 °C for the 2000, 2001 and 2002 study seasons respectively. With the 2001 season being significantly warmer than the 2000 study season. In contrast, the cutover site showed no significant differences in peat temperature at 5 cm depth over the three study seasons, where the seasonal average peat temperatures were 14.4, 14.9 and 14.4 °C for 2000, 2001 and 2002.

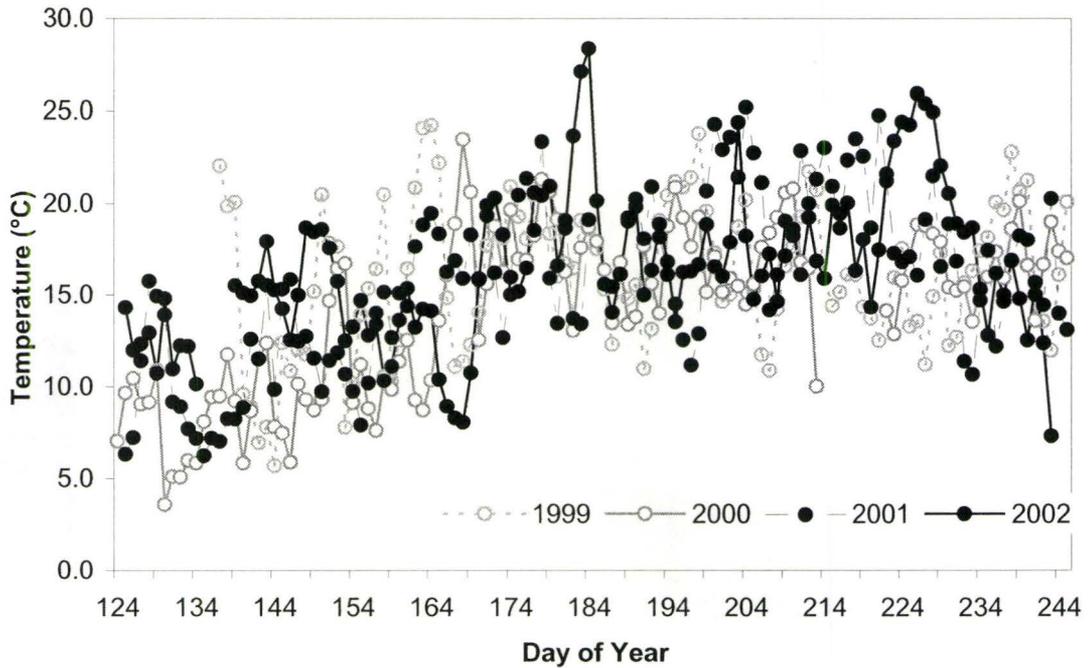


Figure 4.2 Interannual restored site air temperature (°C) (1999, 2000, 2001 and 2002).

Table 4.3: Interannual variability in air temperature compared to the 30-year mean.

Month	T air (°C)				
	30 yr. mean	1999	2000	2001	2002
May	9.1	13.4	8.9	10.6	14.5
June	14.9	16.7	14.8	15.9	14.6
July	17.8	17.1	16.8	18.4	18.1
August	16.5	16.0	16.5	18.1	18.3
<i>Seasonal</i>	<i>14.6</i>	<i>16.2</i>	<i>14.2</i>	<i>15.8</i>	<i>16.5</i>

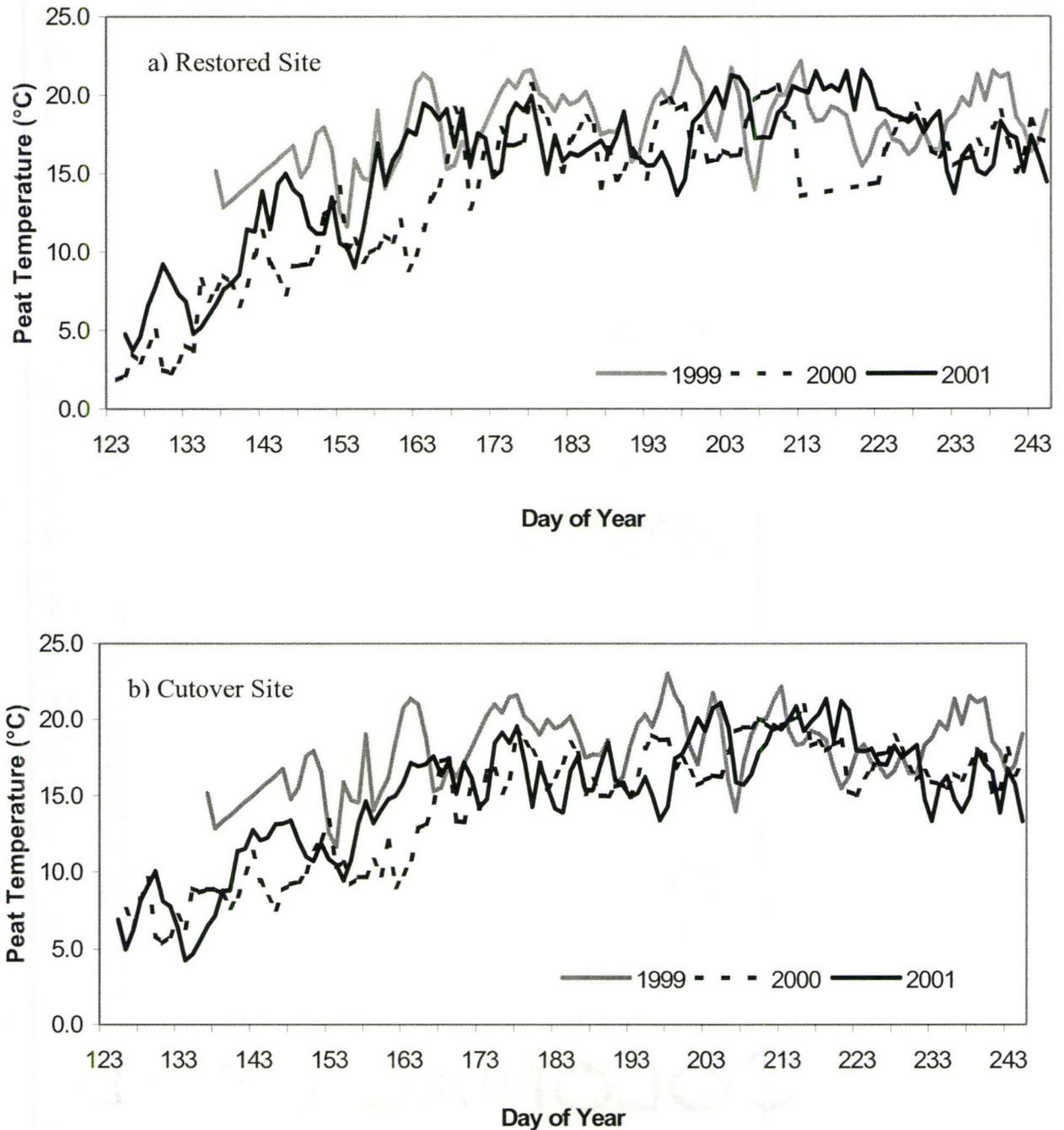


Figure 4.3: Interannual variability in peat temperature (5 cm depth) at the a) restored and b) cutover sites.

In addition to environmental conditions, the changes in surface cover due to vegetation emergence with time post-restoration needs to be accounted for at the restored site. Rapid changes were observed in the percent cover of the restored site, due in part to a decrease in bare peat and a significant increase in vegetation cover. The percent cover of the cutover site did not change significantly between years studied (Figure 4.4). With respect to the restored site, there was a significant decrease in the percentage of bare peat cover from 77.7% in 1999, to 56.7% in 2000 to 18.7% in 2001 and finally to 9.4% in 2002 (Figure 4.4). However there was no change in the percent cover of ditches over the study periods. In terms of vegetation, there were significant increases in the percent cover of both mosses and herbaceous vegetation with time post restoration. Specifically, the percent cover of mosses, mainly *Polytrichum* spp., increased from 4.5% in 1999 to ~ 50% in 2002. While, herbaceous vegetation increased from 13.5% in 2000 due to a complete removal of surface vegetation prior to restoration to 34.9% in 2002. However it should be stressed that this ecosystem is still in transition and it is still in an early stage of succession, however it can be stated that four years post-restoration, there has been rapid emergence of the vegetation at the restored site (Zhou et al., 2005).

4.2 Peat Properties

In terms of peat properties, previous studies have determined that there is not a large range in the bulk density values obtained for both the restored and cutover sites. Specifically, Shantz (2003) determined that bulk density values at Bois-des-Bel ranged from 0.05 to 0.18 g cm⁻³. In addition, von Post degree of decomposition results show that

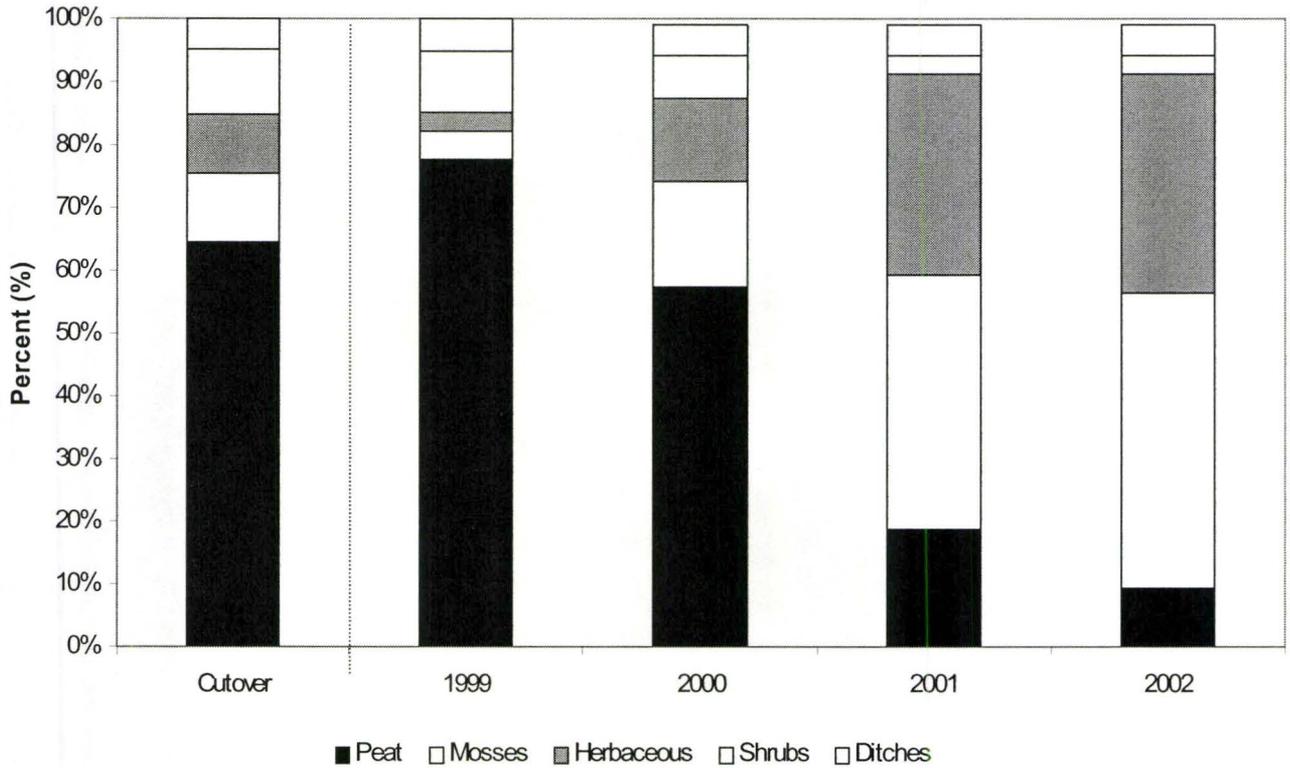


Figure 4.4: Percent cover change at the cutover site (all years) and restored site (1999-2002).

the average degree of decomposition ranged from between 3-5, and increased with depth. For example, the average degree of decomposition at the restored site was H3 at 0-5 cm depth, H4.5 at 5-10 cm depth and lastly, H5 at 10-15 cm.

Furthermore, C:N ratios are larger with increased depth in the peat profile for both the cutover and the restored sites (Figure 4.5), relating to the increased degree of decomposition with depth. For example, the average C:N ratios for the restored site are 49.5 ± 2.4 , 53.6 ± 3.3 and 55.7 ± 5.7 at 0-5, 5-10 and 10-15 cm depths respectively. Whereas average C:N ratios for the cutover site are slightly lower than the restored site at the same depths (48.3 ± 2.9 , 52.1 ± 4.7 and 52.3 ± 2.5). Overall at each depth, both sites are not significantly different from each other. Therefore from the evidence provided it is evident that the peat quality between both the restored and cutover site is still very similar five years post-restoration.

However, there is some within site variability in C:N ratios, dependent mainly on the vegetation present above the soil cores (not shown). For example, the C:N ratios from 0-5 cm depth at the restored site ranged from 45.0 ± 1.9 for *Scirpus*, which was only found in blocked drainage ditches, to 51.1 ± 3.0 for *Sphagnum* spp. As well, in the cutover site, the average peat C:N ratios over 0-5 cm depth ranged from 46.3 ± 2.0 under *Ericaceous* shrubs to 20.3 ± 0.9 under *Polytrichum* mosses.

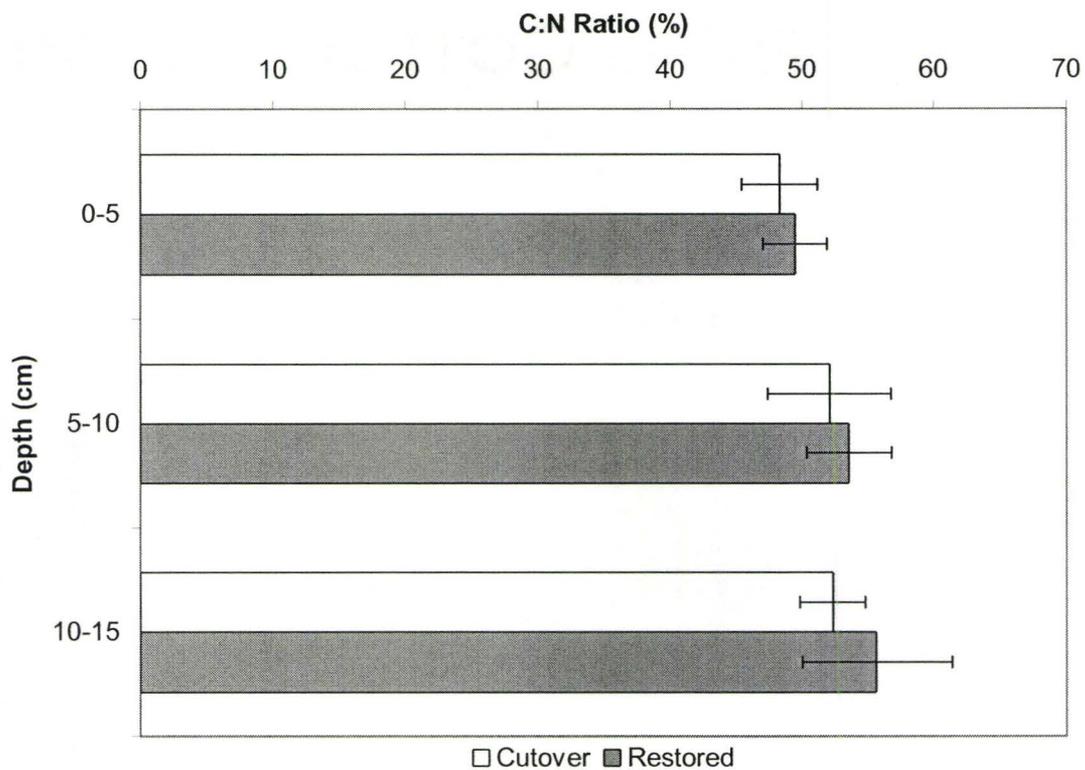


Figure 4.5: Average C:N ratio for both the cutover (white bars) and restored (dark bars) sites.

CHAPTER 5: CO₂ EFFLUX FROM A CUTOVER AND RECENTLY RESTORED PEATLAND

5.1 Introduction

The majority of previous studies conducted in restored peatlands have shown decreased release of CO₂ to the atmosphere with active rewetting, due to a reduction in aerobic decomposition (Waddington and Warner, 2001). A plot scale study conducted by Waddington and Warner (2001), concluded that the restored plot showed more than a two times reduction in the CO₂ released to the atmosphere compared to the abandoned peatlands. However, other studies have demonstrated that post restoration total respiration may increase due to the addition of labile organic matter from a newly established vegetative cover (Croft et al., 2001, Marinier et al., 2004) and straw mulch (Waddington et al., 2003a). However, previous studies fail to determine how the impact of restoration at an ecosystem scale affects peat respiration over time. This chapter characterizes the interannual changes in peat and ditch CO₂ efflux with time post restoration, and compares the fluxes of peat respiration from a restored site to that of an abandoned cutover peatland.

5.2 Results

This chapter only contains results from non-vegetated sites including ditch and peat respiration from pre-restoration (1999) and two years post-restoration (2000 and 2001) to examine the effects of restoration on CO₂ efflux. Peat and ditch fluxes were not measured during the 2002 study season because bare peat only accounted for 10% cover in 2002 (Figure 4.4) allowing for more detailed analysis of the vegetation CO₂ dynamics (Chapter 6).

5.2.1 Pre-Restoration CO₂ Efflux

Both the cutover and the restored sites showed large spatial variability in CO₂ efflux during the 1999 study season with average ditch respiration generally higher than average peat respiration fluxes along the ditch to ditch transects (Figure 5.1). Specifically, the average ditch respiration for the restored and cutover sites were -6.43 ± 4.96 and -8.20 ± 6.80 g CO₂ m⁻² d⁻¹ compared to the average peat fluxes over the same transects of -6.41 ± 6.75 and -5.23 ± 4.22 g CO₂ m⁻² d⁻¹. Lowest fluxes observed for both the cutover and restored sites were located generally at the middle of each transect. For example, the lowest seasonal average flux for the restored site was located at 15 m, or halfway between both ditch locations, with a mean seasonal flux of -3.44 ± 3.94 g CO₂ m⁻² d⁻¹. The largest fluxes were observed at locations with the highest water table depth (Figure 5.1). At the restored transect there was a statistically significant difference in fluxes between the 2 and 5 m and 10 and 15 m collar locations ($P < 0.05$), with the 5 and 15 m collar locations having significantly greater fluxes. All other bare peat sampling locations along the transect were not statistically significantly different from each other ($P > 0.05$),

however, mean seasonal ditch respiration was significantly greater than average seasonal restored site bare peat locations along the restored transect ($P < 0.05$). For the cutover site, seasonal average peat respiration between the 15 to 20 m and 20 to 25 m collar locations were statistically significantly different, where in both cases the 20 m location was significantly greater than the collar locations at 5 m on either side. Finally, the seasonal mean peat fluxes for the restored and cutover sites and average ditch CO_2 fluxes for the cutover and restored sites were not significantly different from each other ($P > 0.05$) during the 1999 study season.

5.2.2 *Response of Peat Respiration Post-Restoration*

In general, peat respiration at both the restored and cutover sites during all study seasons (1999-2001) had low fluxes during the beginning of the study season (Figure 5.2). Whereas fluxes were highest during mid summer, between days 188 and 220, coinciding with peak air temperature values. Peat respiration was highly variable at both the restored and cutover sites, particularly during the 1999 study season. The cutover site had a much larger variability in peat respiration during the 1999 study season compared to both 2000 and 2001. Specifically, peat respiration at the restored site during the 1999 season ranged from -9.0 to $-0.4 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$, resulting in a range of $8.6 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ over the season. However, the cutover site 1999 season peat respiration ranged from -15.3 to $-0.3 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$, resulting in an overall range of $15.0 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$, which was significantly greater compared to the variability at the restored site.

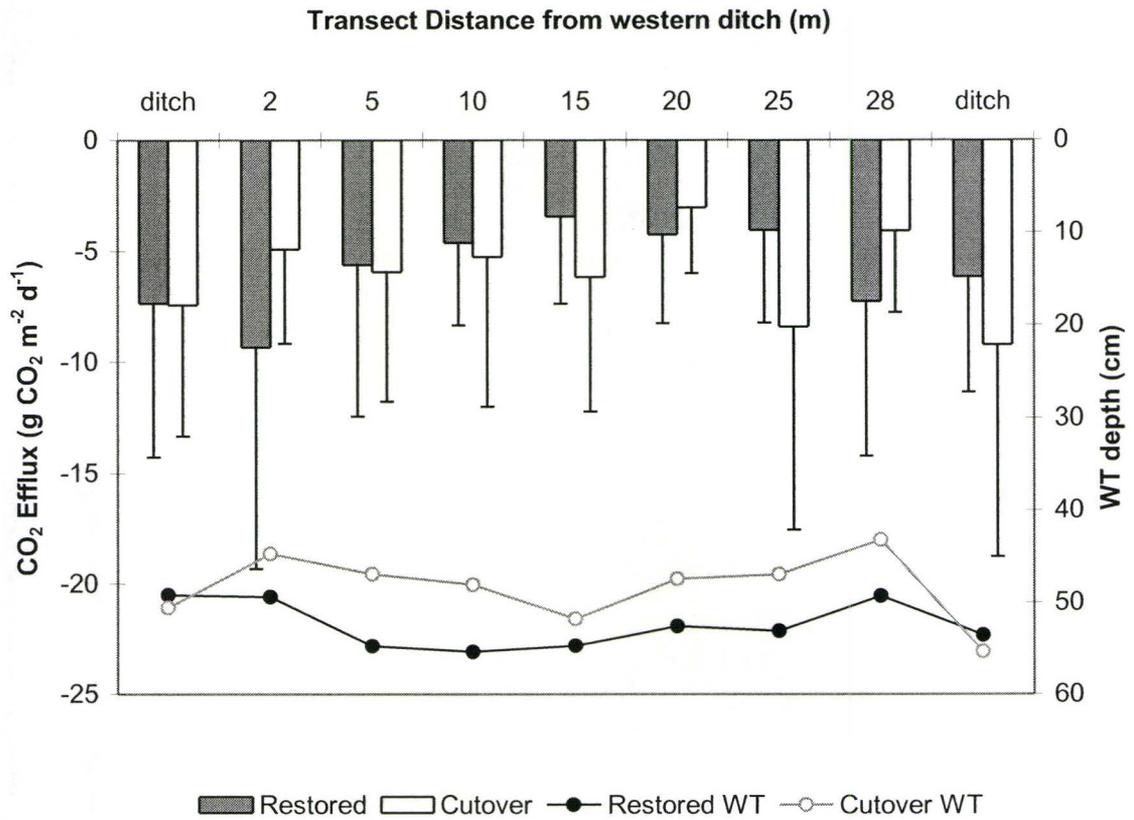


Figure 5.1: Spatial variability in peat and ditch respiration along a peat field transect (western to eastern ditch) at both the restored (dark bars) and cutover sites (white bars) prior to restoration, 1999. Water table (WT) depth is also shown.

In contrast, post-restoration (2000 and 2001) the restored site peat respiration fluxes were more variable as compared to the cutover site. During the 2000 study season, restored site peat respiration ranged from -5.9 to -0.2 $\text{g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$, a significant decrease from the 1999 study season. During the 2001 study season, the restored site peat respiration ranged from -7.8 to -0.1 $\text{g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$, which was not significantly different from the 1999 study season. Even though, the restored and cutover sites show significant differences in interannual and seasonal variability they do not vary significantly from each other in each study season.

5.2.3 Response of Ditch Respiration Post-Restoration

Significant interannual variability in ditch respiration between both the restored and cutover sites (Figure 5.3) was observed in all three-study seasons. Similar to the peat respiration, fluxes increased at both the restored and cutover sites during all study periods in late July and early August, when there are lower water table levels observed in the ditches. The 1999 study season showed the greatest variability in fluxes for both the restored and cutover sites. For example, the restored site ditch respiration ranged from -18.7 to -1.1 $\text{g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ whereas, the cutover site ranged from -17.5 to -0.2 $\text{g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$. Moreover, the cutover site experienced the largest variability for both the 2000 and 2001 study seasons.

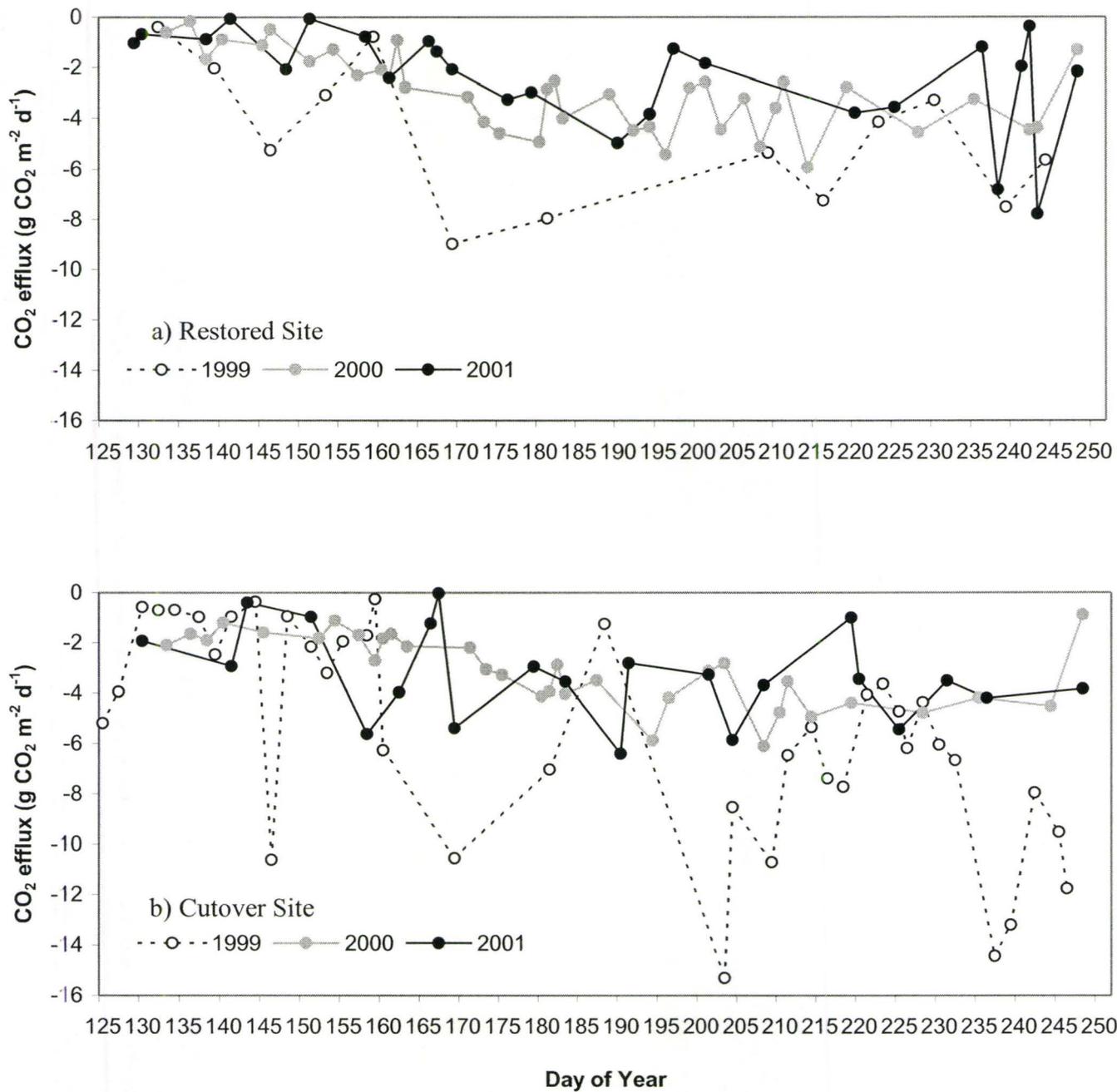


Figure 5.2: Bare peat respiration for 1999 (open), 2000 (grey) and 2001 (black) at the a) restored and b) cutover sites.

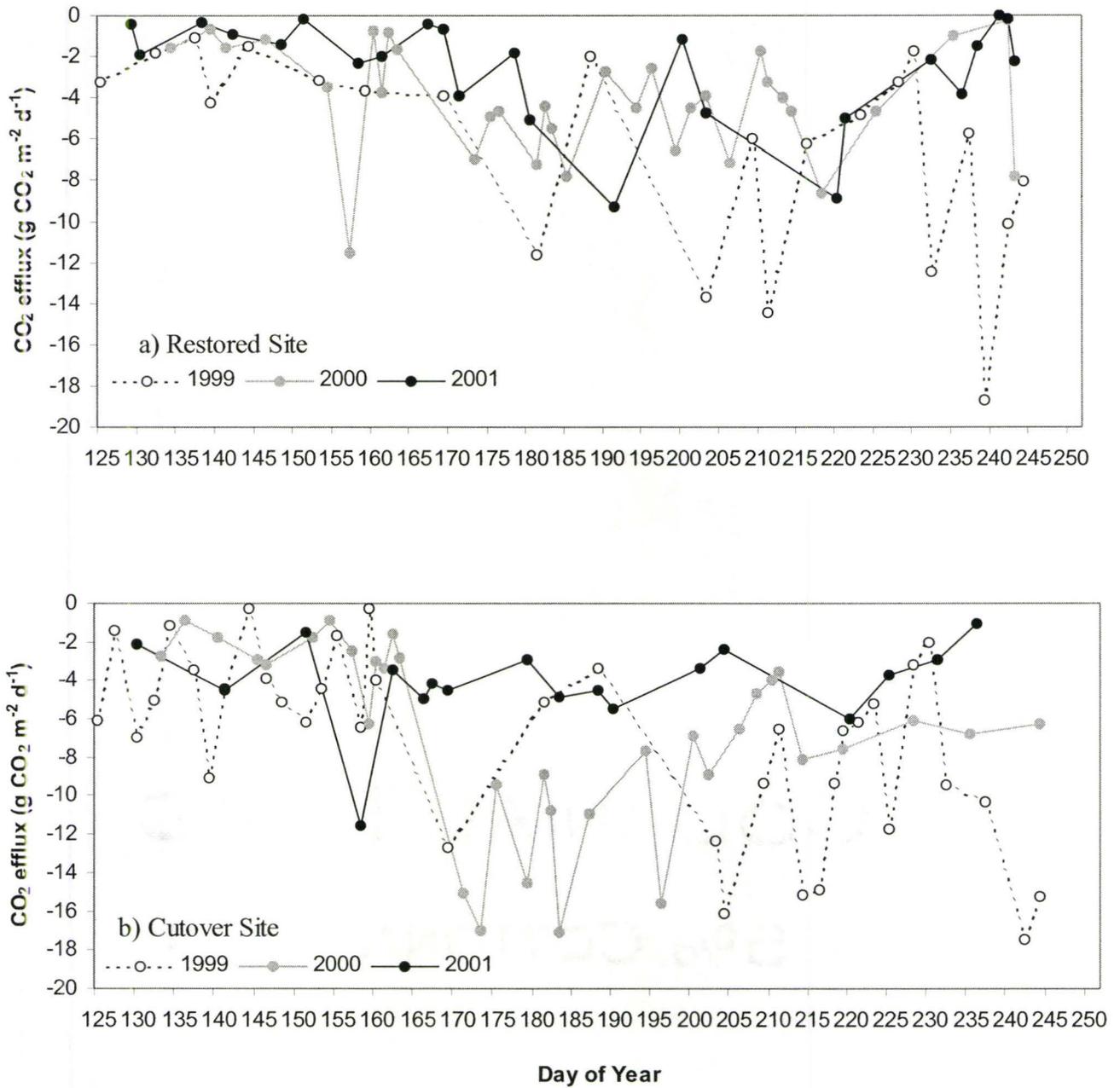


Figure 5.3: Ditch respiration for 1999 (open), 2000 (grey) and 2001 (black) at the a) restored and b) cutover sites.

5.2.4 Relationships with Environmental Variables

5.2.4.1 Temperature

During the 2000 study season the restored site had the best relationship between average peat respiration and air temperature, as it explained 74% of the variability in peat respiration (Figure 5.4). However, both 1999 and 2001 study seasons showed poor relationships between restored site average peat respiration and air temperature with R^2 values of only 0.09 and 0.33 respectively. The cutover site also had the best linear regression relationship between daily average air temperature and peat respiration during the 2000 study season ($R^2 = 0.67$). Similar to the restored site, the cutover site also displayed poor negative relationships between peat respiration and air temperature during both the 1999 and 2001 study seasons (R^2 values of 0.12 and 0.08 respectively). However, the corresponding slope values determined for each of these linear regression relationships varied significantly between each study period, pre and post-restoration as well as between the two study sites. The slope of the restored site linear regression equations became steeper with time, -0.19 in 1999 to -0.28 in 2000 and finally -0.33 in 2001. In contrast, the slope estimates for the cutover site actually decreased with time from -0.36 in 1999 to -0.25 in 2000 and lastly, -0.15 in 2001. Overall, there were no significant relationships ($R^2 > 0.7$) between air temperature and peat respiration at both the restored and cutover sites in each year studied.

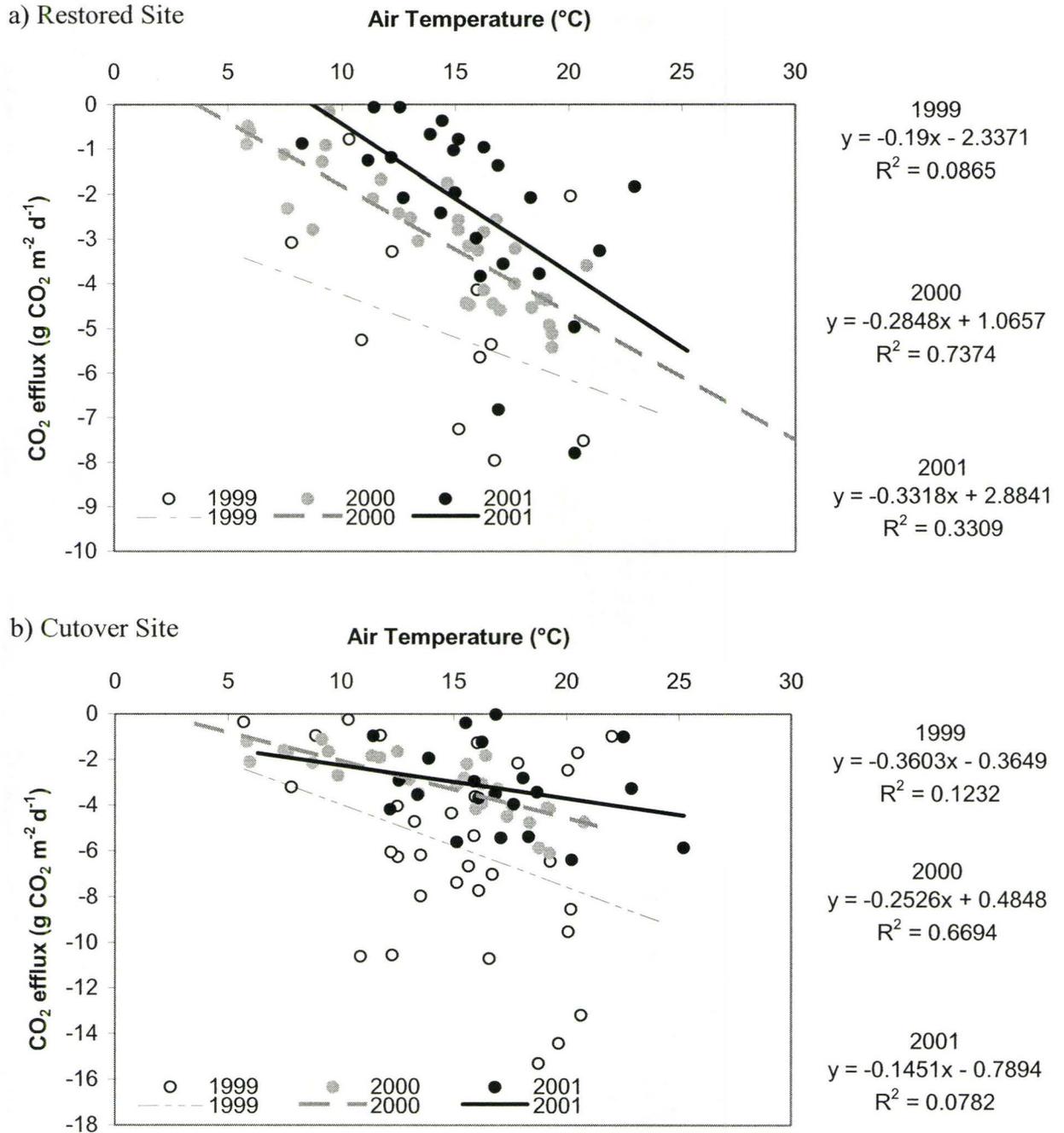


Figure 5.4: Relationship between average peat respiration and air temperature at the a) restored and b) cutover sites.

5.2.4.2 Soil Moisture

The linear regression relationships between seasonal average peat respiration and soil moisture at the restored and cutover sites were also not significant ($R^2 < 0.7$) (Figure 5.5). With soil moisture explaining only 15% and 5% of the variability in peat respiration at the restored and cutover sites respectively during the 2001 study season. Moreover, no significant relationships ($R^2 > 0.7$) were observed between the multiple regression analysis of soil moisture and air temperature or between soil moisture and peat temperature at various depths (Table 5.1). The best multiple regression relationship explained 25% of the variability in 2001 cutover site peat respiration, was between soil moisture and air temperature.

In summary, poor regression relationships result from the large inherent variability with the fluxes at this site both spatially (Figure 5.1) and temporally (Figures 5.2 and 5.3). However, when regression models were calculated on an individual collar by collar basis (analysis not shown), air temperature and soil moisture explain a greater degree of variation in CO₂ efflux.

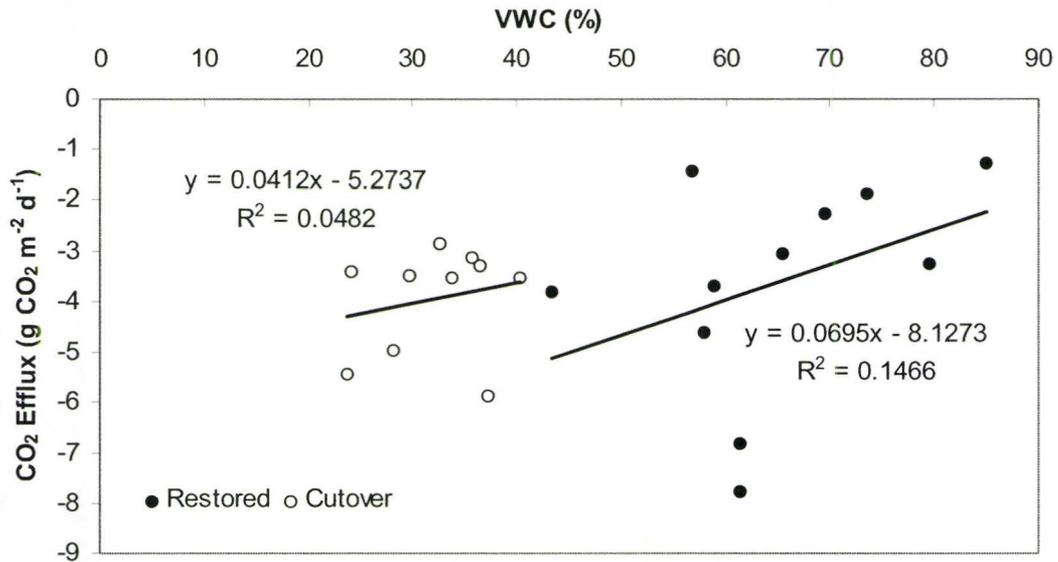


Figure 5.5: Relationship between peat respiration and VWC (%) for both the cutover (open) and restored site (black) in 2001.

Table 5.1: Multiple linear regression relationships between air temperature, peat temperature and soil moisture at both restored and cutover sites in 2001.

		Restored Site		Cutover Site	
x1	x2	Equation	R ²	Equation	R ²
VWC	Tair	$y = -3.60 + 0.0197 \cdot \text{VWC} - 0.0455 \cdot \text{Tair}$	0.08	$y = -2.78 + 0.0415 \cdot \text{VWC} - 0.162 \cdot \text{Tair}$	0.25
VWC	T2	$y = -2.34 + 0.0043 \cdot \text{VWC} - 0.075 \cdot \text{T2}$	0.11	$y = -8.51 + 0.0716 \cdot \text{VWC} + 0.012 \cdot \text{T2}$	0.15
VWC	T5	$y = -2.52 + 0.0085 \cdot \text{VWC} - 0.086 \cdot \text{T5}$	0.10	$y = -7.0 + 0.0641 \cdot \text{VWC} - 0.041 \cdot \text{T5}$	0.15
VWC	T10	$y = -1.03 + 0.0039 \cdot \text{VWC} - 0.183 \cdot \text{T10}$	0.11	$y = -11.6 + 0.0815 \cdot \text{VWC} + 0.160 \cdot \text{T10}$	0.16

5.2.5 *Interannual Mean Seasonal Peat Respiration*

Mean peat respiration fluxes from both the cutover and restored site (Figure 5.6) were not statistically significantly different from each other in each study year ($P > 0.05$). However, when comparing between years, the cutover site showed no significant changes in mean peat respiration over time. Conversely, the restored site showed a significant decrease in mean peat respiration post-restoration, due in part to active rewetting. In 1999, prior to restoration, the cutover site with a mean peat CO_2 efflux of $-5.36 \pm 4.11 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ was not statistically significantly different ($P > 0.05$) from the restored site with a seasonal mean of $-4.74 \pm 2.75 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$. Therefore, the cutover site provides a good baseline from which to compare changes at the restored site in years following restoration. Furthermore, both the cutover and restored site bare peat respiration decreased over time post 1999. Specifically, the restored site peat respiration significantly decreased ($P < 0.05$) by 36% between 1999 and 2000. As well there was a significant 23% decrease in the flux from 2000 to 2001 ($P < 0.05$). Hence, the mean seasonal peat CO_2 efflux at the restored site decreased by as much as ~50% from 1999 to 2001, two years post restoration. However when comparing with the seasonal average peat respiration from the cutover site, the fluxes are not statistically significantly different between each year studied. Mean seasonal fluxes for the cutover site were $-5.63 \pm 4.11 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$, $-3.44 \pm 1.89 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ and $-3.26 \pm 1.85 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ in 1999, 2000 and 2001 respectively. With a percent decrease of ~40% between 1999 and 2000, and only a ~3% decrease between 2000 and 2001.

5.2.6 *Interannual Mean Seasonal Ditch Respiration*

Mean seasonal ditch respiration fluxes were greater than bare peat fluxes, with average seasonal fluxes ranging from -2.51 ± 2.55 to -7.07 ± 4.73 g CO₂ m⁻² d⁻¹. Ditches at both the cutover and restored site showed significant decreases ($P < 0.05$) in mean seasonal respiration pre-restoration (1999) to two years post restoration (2001) (Figure 5.7). Moreover, the 1999 seasonal mean ditch respiration for the cutover and restored site were not significantly different ($P > 0.05$) from each other with seasonal means of -7.07 ± 4.73 and -6.43 ± 4.96 g CO₂ m⁻² d⁻¹ respectively. The cutover site showed no significant change ($P > 0.05$) in ditch respiration for both 2000 and 2001, with mean values of -6.77 ± 4.75 g CO₂ m⁻² d⁻¹ and a 17% decrease in flux and -4.11 ± 2.29 g CO₂ m⁻² d⁻¹, and a ~40% decrease in flux respectively. In contrast, the restored site displayed significant decreases ($P < 0.05$) in the ditch respiration post-restoration with a 40.4% decrease from 1999 to 2000 and a 34.5% decrease from 2000 to 2001, and an overall decrease of 61.0% from pre-restoration to two years post restoration. Furthermore, mean ditch respiration for the cutover site was significantly greater than the restored site in both the 2000 and 2001 study seasons.

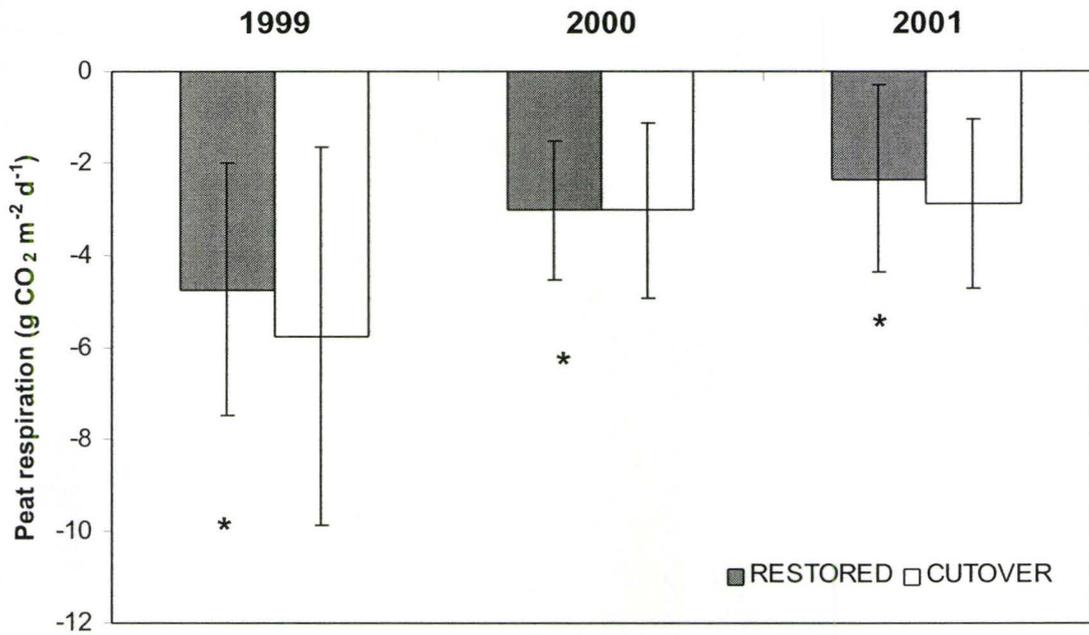


Figure 5.6: Seasonal average peat respiration from the restored (dark bars) and cutover sites (white bars) in 1999, 2000 and 2001. Asterisks indicate sites that are significantly different between years ($P < 0.05$).



Figure 5.7: Seasonal average ditch respiration from the restored (dark bars) and cutover sites (white bars) in 1999, 2000 and 2001. Asterisks indicate sites that are significantly different between years ($P < 0.05$).

5.3 Discussion

5.3.1 *Pre-Restoration CO₂ Efflux from Bare Peat and Ditches*

Prior to restoration, results from the 30 m ditch to ditch transect at both the restored and cutover site showed significant spatial variability in CO₂ efflux. Prior to restoration, the largest CO₂ fluxes observed were from bare peat locations with the highest water table depth, consequently locations with a close proximity to ditches. Whereas the lowest fluxes observed for both the cutover and restored transects were from bare peat located at the relative midpoint of each transect, with these locations having the greatest depth to the water table. These results suggest that a reduction in CO₂ efflux from bare peat locations with large water table depths are suffering drought stress, and as a consequence, reduced microbial activity (Lomander et al., 1998; Subke et al., 2003). Therefore, the ditches supply moisture to stimulate microbial activity in nearby peat transect locations, at the same time, these drainage ditches may provide a source of labile carbon for microbial consumption in the form of DOC (Tóth, 2002).

Similar to seasonal respiratory fluxes from bare peat surfaces, seasonal mean peat and average ditch CO₂ fluxes for both the cutover and restored sites along the 30 m transects were not significantly different from each other ($P > 0.05$) during the 1999 study season. As was previously discussed, both the restored and cutover sites have similar catotelmic peat quality and degree of humification, after five years post-restoration, which ultimately leads to no significant differences in fluxes from non-vegetative sites.

5.3.2 *Response of Peat Respiration Post-Restoration*

With time post-restoration restored site peat respiration significantly decreased ($P < 0.05$) by 36% and 23% between 1999 to 2000 and 2000 to 2001, respectively due to active rewetting. Overall, the mean seasonal peat efflux at the restored site decreased by as much as ~50% from 1999 to 2001. This decrease can be attributed to a reduction in aerobic decomposition from an increased water table depth as well as a significant increase in soil moisture conditions at the restored site post rewetting (Shantz, 2003). Therefore, active rewetting at the restored site created a reduction in the aerobic zone and ultimately a reduction of peat oxidation, as well as a reduction in diffusive transport of CO_2 to the atmosphere (Jackson, 1985). However, these results are in contrast to previous studies that suggest that active restoration can lead to an increased CO_2 production potential. For example, an incubation study conducted by Grunier (2003) determined that CO_2 production potential of restored peat increased due to increased labile carbon present in restored peatland from decomposing straw mulch cover as well as emerging vegetation surface. However, the restored peat still had lower CO_2 production potential when compared to a natural peatland (Grunier, 2003). Similarly, Croft et al., (2001) and Marinier et al., (2004) determined that microbial activity was stimulated with restoration as a result of increased labile carbon present from emerging vegetation inputs at these sites compared to those that remain abandoned.

Conversely, this study indicates that the seasonal average peat respiration from both the restored and cutover sites were not statistically significantly ($P > 0.05$) different between each year studied. It is suggested that these sites display similar fluxes two

years post-restoration due to similarities in peat substrate quality. Due to the nature of peat harvesting, both sites have similar underlying, catotelmic peat substrates. As well, both sites have a similar degree of humification as well as nutrient concentrations as displayed by C:N ratios (Figure 4.5).

Despite the similarity of the seasonal average fluxes in peat respiration for both the restored and cutover sites, the cutover site still displays greater variability in daily average peat respiration, likely due to larger seasonal and diurnal variations in peat temperature in cutover peat (Price et al, 1998). Similarly, in abandoned, cutover sites the majority of labile carbon stores have been removed, leaving behind degraded catotelmic peat whose mineralization is less sensitive to temperature changes (Updegraff et al., 1998). However, due to active restoration, the restored site had a straw mulch cover that moderates temperature fluctuations within the peat (Petronne et al., 2001) as well as the response of temperature to peat respiration.

The largest seasonal flux for both the restored and cutover sites was during the warmer 1999 study season, suggesting that interannual climatic variability is the dominant control for changes in peat respiration at this stage of restoration. Therefore at the current period of time post-restoration at Bois-des-Bel there is an apparent trade-off between a reduction in aerobic decomposition and diffusive transport associated with rewetting at the same time as an increased CO₂ production potential and microbial activity caused by increased labile carbon availability from both a decomposing mulch layer (Waddington et al., 2003a) and an emerging vegetation cover.

5.3.3 *Response of Ditch Respiration Post-Restoration*

At both the cutover and the restored sites, respiration fluxes from ditches are greater in magnitude compared to the respiration of bare peat. These sites are wetter, which aids in microbial functioning (Lomander et al., 1998; Subke et al., 2003). Moreover, blocked drainage ditches at the restored site represent a fresh labile carbon source as they contain shrub and tree debris removed during restoration. A study conducted by Tóth (2002) determined that these restored site ditches were a large source of DOC, a source of labile carbon ultimately creating a temporal microbial hot spot.

However, in contrast the present study found that seasonal average ditch respiration at the restored site actually decreased with time post-restoration, by ~40% between 1999 and 2000 and ~35% between 2000 and 2001 study seasons. Even though there was a fresh source of labile carbon to support microbial activity in restored site ditches, the impact of rewetting had a greater effect by reducing the net diffusive flux of CO₂ to the atmosphere in these locations (Jackson, 1985). In addition, research conducted by Day (2003), determined that post-restoration, ditch locations were a large source of methane to the atmosphere, due in part to rewetting and an increased anaerobic zone in the blocked drainage ditches, as well from a large labile carbon source for methanogenesis at these locations.

Moreover, pre-restoration both the cutover and restored site seasonal mean ditch respiration fluxes were not statistically significantly different from each other; again due to similar hydrological conditions and peat character prior to restoration. Similar to the peat respiration, fluxes increased at both the restored and cutover sites during all study

periods in late July and early August, when there were lower water table levels observed in the ditches. A reduction in water table depth allows for increased rates of aerobic decomposition as well as enhanced rates of diffusion of CO₂ to the atmosphere.

5.3.4 *Relationship With Environmental Variables*

Regression relationships between environmental variables, namely air temperature and soil moisture and peat respiration at both the restored and cutover sites displayed poor relationships as a result of the large inherent variability in respiratory fluxes both spatially and temporally at the site. Overall, there were no significant relationships ($R^2 > 0.7$) between air temperature and peat respiration at both the restored and cutover sites in each year studied. At the restored site, the 2000 study season had the best relationship between average peat respiration and air temperature, as it explained 74% of the variability in peat respiration. In contrast, relationships with soil moisture only explained 15% and 5% of the variability in peat respiration at the restored and cutover sites respectively during the 2001 study season. These poor relationships are in contrast to previous studies that generally find peat temperature a strong determinant of peat respiration. It has been suggested that increased temperatures increase the potential for oxidation (Moore and Dalva, 1993). According to Bridgham and Richardson (1992), soil temperature explained 67-84% of the variability of the variability in peat CO₂ emissions. However, Bridgham and Richardson (1992), also determined that soil moisture was insignificant in explaining CO₂ emissions, as was found in this study. Furthermore, previous studies also suggest that peat soil temperature is probably most important under

very wet conditions early in both seasons, but the peat moisture increases in importance under drier conditions (Linn and Doran, 1984). As such, the slope of the relationship between air temperature and peat respiration increased with time post-restoration, suggesting that as hydrologic conditions were improving with time post-restoration at Bois-des-Bel (Shantz, 2003), the importance of temperature to explain the variability in peat respiration was also increasing. Furthermore, when regression models were calculated on an individual collar-by-collar basis, air temperature and soil moisture explained a greater degree of variation in CO₂ efflux as compared to seasonal average estimates which suggests small scale differences in peat quality are important.

5.3.5 *Implications for restoration*

One of the main goals of peatland restoration is to return the natural carbon sink function of these sites, by a reduction in peat decomposition as well as an increase in plant productivity at the site. It is essential to determine how restoration affects the rates of peat respiration to assess if the site will return to a net long-term carbon sink, and similarly, to create appropriate restoration techniques and management to achieve this goal. Results of peat respiration at Bois-des-Bel indicates that the seasonal average fluxes are decreasing with time post-restoration which is encouraging for the peat industry that active restoration is successful at reducing peat respiration. However at the same time the peat respiration fluxes from the restored site are not statistically significantly different from those at the cutover site. Therefore, at the current stage in restoration there is a trade-off between a reduction in aerobic decomposition and diffusive transport via active

rewetting at the restored site and an increase in microbial activity and CO₂ production potential, making the seasonal average peat efflux not significantly different between sites two years post-restoration.

As for ditch respiration, on average they represent a larger source of CO₂ efflux as compared to peat respiration due to a source of labile carbon and moisture for microbial processes present. However, after two years post-restoration the restored site ditches have a lower flux as compared to the cutover site, therefore the reduction in seasonal flux of ditch respiration is not attributed to an increase in labile carbon but to a decrease in diffusive flux as a result of active rewetting. As well, they only account for 5% of the peatland area, and therefore will not significantly affect the overall CO₂ budget at the site with time post-restoration. Consequently for serious changes in the carbon balance to occur post-restoration requires the emergence and development of peatland vegetation.

CHAPTER 6: VEGETATION NET ECOSYSTEM EXCHANGE FROM A CUTOVER AND RECENTLY RESTORED PEATLAND

6.1 Introduction

Most studies conducted in restored peatlands have shown a decreased release of CO₂ to the atmosphere with active rewetting, due to a reduction in aerobic decomposition (Waddington and Warner, 2001). A plot scale study conducted by Waddington and Warner (2001), concluded that the restored plot showed more than a two times reduction in the CO₂ equivalents released to the atmosphere compared to abandoned peatlands. It was estimated that 70% of this decrease in CO₂ emissions post-restoration was due to an increase in GEP and 30% was due to a decrease in soil respiration (Waddington and Warner, 2001). European studies have also seen a reduction in CO₂ efflux post-restoration. A study conducted by Tuittila et al. (1999), found that active rewetting decreased respiration as well as increasing productivity at the site, specifically from *Eriophorum* species. Even two years post-restoration, this study determined that the site became a net sink of atmospheric CO₂ from a dense *Eriophorum* cover. Similarly, Komulainen et al. (1999), found that rewetting drained peatlands increased *Eriophorum* cover and ultimately changed the seasonal carbon balance towards an increase in CO₂ sequestration. However, previous studies have not examined the effect of site scale ecosystem restoration and the continual emergence of vegetation cover have on changes in net ecosystem exchange with time post-restoration. This chapter characterizes the spatial and temporal variability of net ecosystem exchange of CO₂ at a cutover and recently restored peatland ecosystem; specifically examining the CO₂ exchange between

different vegetation types; as well as to determine the dominant ecohydrological processes controlling CO₂ exchange at the restored site.

6.2 Results

6.2.1 *Response of Moss Vegetation Net Ecosystem Exchange Post-Restoration*

Prior to restoration (1999) and active rewetting, it was assumed that moss vegetation at both the cutover and restored sites would display similar NEE fluxes. Therefore, 1999 seasonal mean moss NEE was -5.62 ± 4.64 g CO₂ m⁻² d⁻¹ (Figure 6.1), a seasonal source of CO₂, as measured at the cutover site was also set as the baseline restored site value. With time post-restoration at the restored site there was a statistically significant ($P < 0.05$) increase in positive NEE and ultimately the CO₂ sink strength of moss vegetation with an overall increase from -5.62 ± 4.64 g CO₂ m⁻² d⁻¹ in 1999 to 6.62 ± 4.12 g CO₂ m⁻² d⁻¹ in 2002. Between pre (1999) and one year post-restoration (2000) there was a significant ($P < 0.05$) increase in seasonal average moss NEE to an overall seasonal flux of -1.06 ± 2.03 g CO₂ m⁻² d⁻¹, a change in 4.6 g CO₂ m⁻² d⁻¹. However, restored site moss vegetation still remained a seasonal source of CO₂ to the atmosphere during 2000. In contrast, restored site moss NEE displayed a positive flux during the 2001 study season, with a seasonal mean of 4.12 ± 3.32 g CO₂ m⁻² d⁻¹. This resulted in a significantly greater ($P < 0.05$) seasonal mean NEE, with an overall increase of 5.0 g CO₂ m⁻² d⁻¹ as compared to 2000. During the 2002 study season, the restored site seasonal average moss NEE continued to increase with a seasonal mean of 6.62 ± 4.12 g CO₂ m⁻² d⁻¹.

In contrast, the cutover site showed no significant changes in seasonal average moss NEE between all study seasons. As well, seasonal average cutover site moss NEE

remained negative (dominated by respiration) over all study seasons. Specifically, the 2000 seasonal average moss NEE was not statistically significantly different ($P > 0.05$) from pre-restoration (1999) fluxes, with a seasonal average of $-3.46 \pm 2.98 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$. The 2001 seasonal average cutover moss was not significantly different ($P > 0.05$) as compared to the 2000 study season, even though there was an ~50% decrease in the net release of CO_2 to the atmosphere. In contrast, during the 2002 study season, the seasonal mean NEE flux significantly ($P < 0.05$) decreased by almost 400% as compared to the 2001 study season, with a seasonal average of $-8.34 \pm 8.68 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$.

When comparing the seasonal average moss NEE between the restored and the cutover site, with the exception of the 2002 study season, the sites were not statistically significantly different ($P > 0.05$) from each other, despite the fact that during 2001 and 2002 the restored site had positive seasonal NEE and the cutover site had slightly negative seasonal NEE fluxes.

The restored site seasonal average moss respiration displayed large interannual variability with time post restoration (Figure 6.2). Fluxes ranged from $-4.02 \pm 2.30 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ in 2000 to $-12.43 \pm 4.48 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ in 2002. In particular, there was a significant decrease ($P < 0.05$) in seasonal average restored site moss respiration between 1999 and one-year post restoration (2000), relating to a 43% decrease. As well, there was a significant increase in seasonal average restored site moss respiration between 2001 and 2002 by ~105%.

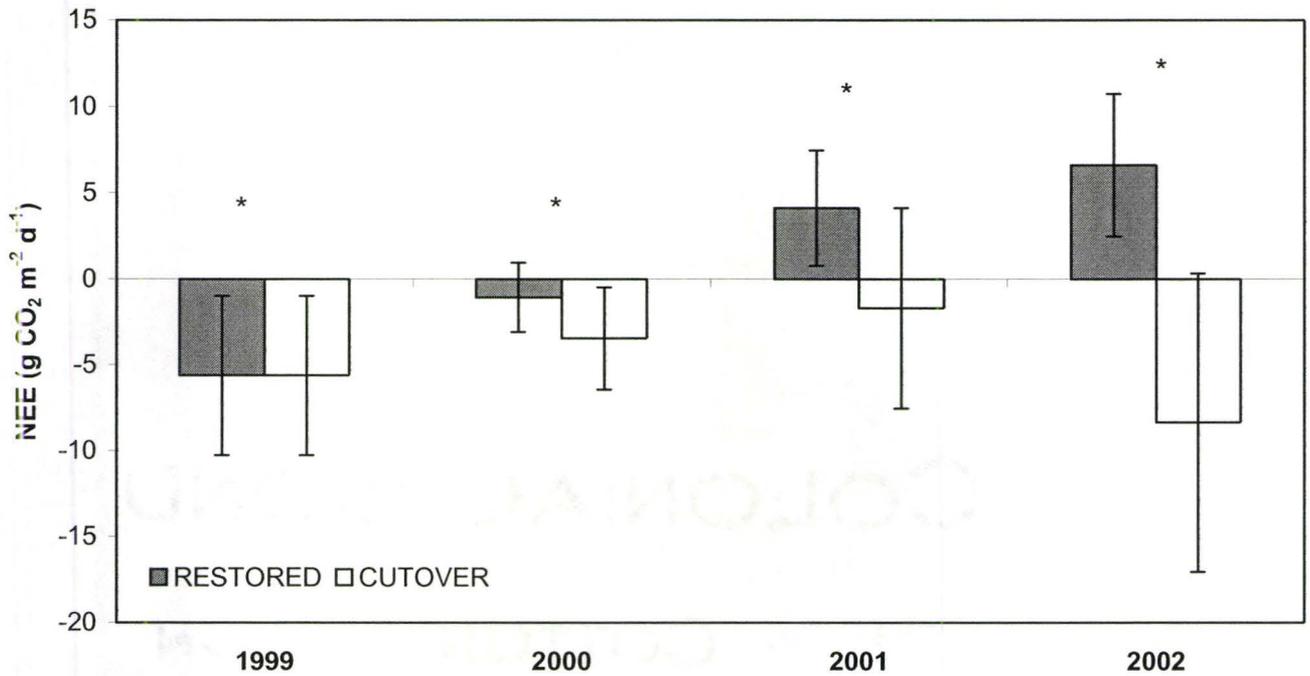


Figure 6.1: Seasonal average moss vegetation net ecosystem exchange (NEE) from the restored (dark bars) and cutover sites (white bars), from 1999-2002. Asterisks indicate sites that are significantly different between years ($P < 0.05$).

At the same time as changes in respiration were occurring post-restoration there was also a significant increase in productivity over time (Figure 6.2). There was a clear increasing trend in the restored site in years following restoration with a statistically significant ($P < 0.05$) ~200% increase in productivity between 2000 and 2001 and a ~75% increase between 2001 to 2002. Overall, seasonal average moss GEP at the restored site increased from $6.07 \pm 5.25 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ in 1999 to $18.50 \pm 6.01 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ in 2002, three years post-restoration. Nevertheless, there was a statistically significant ($P < 0.05$), (42%) decrease in GEP between 1999 and 2000, due to the removal of all surface vegetation during the restoration process.

For the cutover site, there was no significant difference ($P > 0.05$) in production between all four study seasons as fluxes ranged from $6.07 \pm 5.25 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ in 1999 to $9.62 \pm 4.64 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ in 2000. However, the cutover site respiration component of moss NEE, was statistically significantly ($P < 0.05$) different between the 1999 and 2000 and the 2001 and 2002 study seasons, representing a 57% and 54% increase respectively. As such, the cutover site moss seasonal mean respiration varied from $-13.65 \pm 6.34 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ in 2002 to $-7.70 \pm 3.90 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ in 1999.

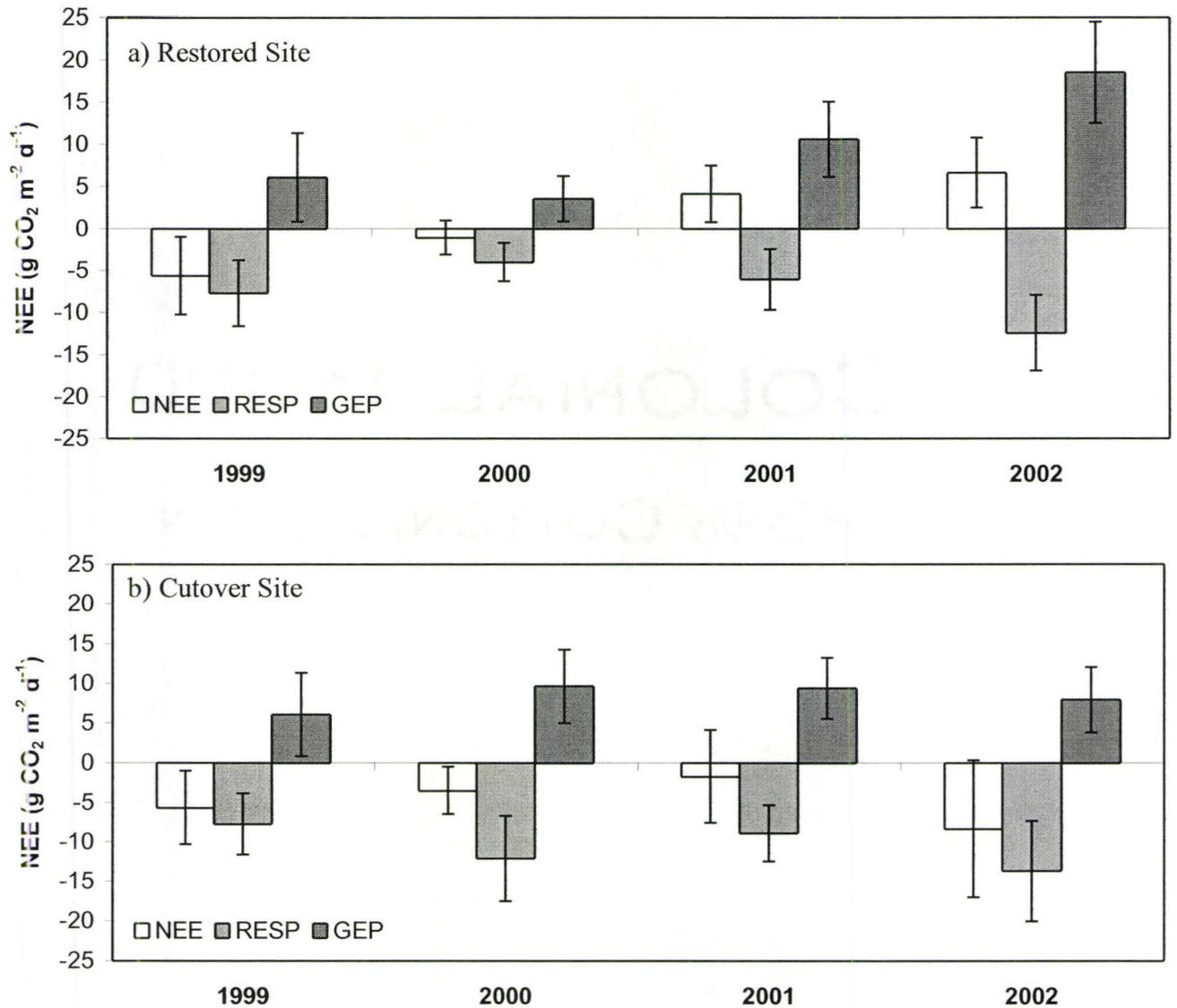


Figure 6.2: Seasonal average moss net ecosystem exchange (NEE) (white bars), respiration (grey bars) and gross ecosystem production (GEP) (dark bars) at the a) restored and b) cutover sites from 1999-2002.

6.2.2 *Response of Herbaceous Vegetation Net Ecosystem Exchange Post-Restoration*

The seasonal average herbaceous vegetation NEE fluxes, mainly consisting of *Eriophorum spp.*, were much larger in magnitude compared to moss locations (Figure 6.3). Similar to moss NEE fluxes the 1999 seasonal average herbaceous fluxes for both the restored and cutover site were assumed to be equal, as no active restoration had occurred. The seasonal average herbaceous vegetation NEE during 1999, as measured at the cutover site was $7.91 \pm 6.56 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$, a net sink of atmospheric CO_2 . Post-restoration, the restored site showed a large interannual variability in seasonal average herbaceous NEE fluxes ranging from $2.40 \pm 8.85 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ in 2001 to $18.02 \pm 4.48 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ in 2000. Furthermore, restored site herbaceous seasonal mean NEE fluxes were positive during each study season, creating a seasonal net uptake of CO_2 . There was a statistically significant ($P < 0.05$) increase in NEE between 1999 and only one year post-restoration (2000), ultimately resulting in a ~130% increase in CO_2 sequestration for restored site herbaceous vegetation. However, during the 2000 and 2001 study seasons, there was a statistically significant ($P < 0.05$) drop in seasonal average herbaceous NEE. The flux remained positive during the 2001 study season, however it resulted in a ~90% decrease in NEE two years post restoration. Furthermore, the restored site herbaceous seasonal average NEE increased by ~275% between 2001 and 2002.

In contrast, the cutover site herbaceous vegetation had a net release of CO_2 , during both the 2001 and 2002 study seasons, with seasonal average fluxes of $-2.03 \pm 2.23 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ and $-1.18 \pm 3.38 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ respectively. However, during the 1999 and 2000 study seasons, cutover herbaceous vegetation was an overall net sink of

atmospheric CO₂. Nevertheless, there was a statistically significant ($P < 0.05$) decrease in the NEE between the 1999 and 2000 study seasons, by ~80%. However, during all years post-restoration: 2000-2002, there was no statistically significant ($P > 0.05$) difference in seasonal average herbaceous NEE at the cutover site as fluxes ranged from 1.77 ± 4.03 g CO₂ m⁻² d⁻¹ in 2000 to 2.03 ± 2.23 g CO₂ m⁻² d⁻¹ in 2001.

When the seasonal average herbaceous NEE fluxes at both the restored and cutover sites were compared, there were significant differences ($P < 0.05$) between fluxes in both the 2001 and 2002 study seasons, with a range in fluxes of 4.43 and 10.20 between years respectively. In both the study seasons the restored site NEE was greater than the cutover site.

Restored site herbaceous productivity remained fairly high during all study seasons ranging from 12.82 ± 6.73 g CO₂ m⁻² d⁻¹ in 2001 to 30.34 ± 10.53 g CO₂ m⁻² d⁻¹ during 2000 (Figure 6.4). However, there was a significant ~60% decline in herbaceous production between one and two years post-restoration. This reduction in productivity is reflected in the substantial decrease in restored site NEE between 2001 and 2001 (Figure 6.3). Additionally, there was significant ($P < 0.05$) increase in the production from the seasonal average minimum 2001 flux to 26.22 ± 5.03 g CO₂ m⁻² d⁻¹ in 2002, resulting in an 105% increase over two study seasons.

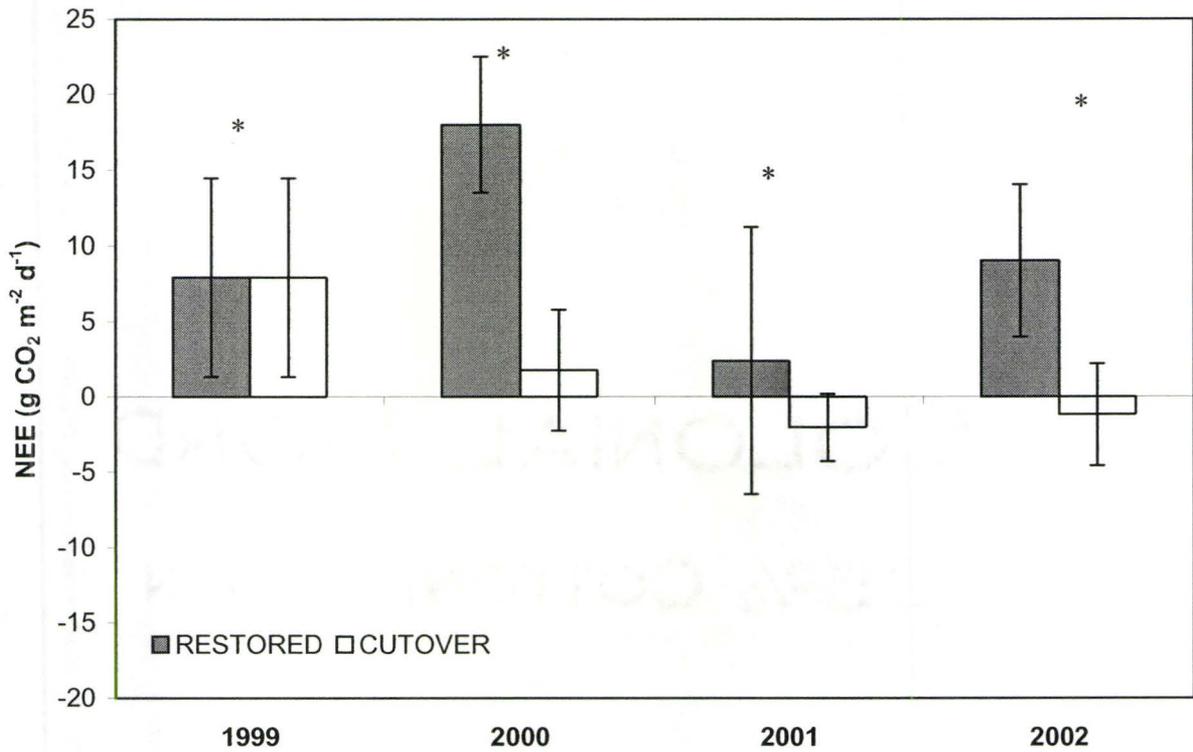


Figure 6.3: Seasonal average herbaceous vegetation net ecosystem exchange (NEE) from restored (dark bars) and cutover sites (white bars) from 1999-2002. Asterisks indicate sites that are significantly different between years ($P < 0.05$).

As for herbaceous respiration at the restored site there was a significant decrease of 35% between pre (1999) and one-year post restoration (2000). However there were no significant changes in respiration between 2000 and 2001, with seasonal average fluxes of $-12.34 \pm 7.75 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ and $-9.27 \pm 7.97 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$, respectively. Furthermore, there was a significant ($P < 0.05$) increase in respiration during the 2002 study season, by ~105 % from 2001.

In the cutover site there was a large interannual variability in production over time, with a range of $4.31 \pm 2.37 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ in 2001 to $27.02 \pm 13.94 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ in 1999. Specifically, a significant ($P > 0.05$) 60% and 62% decrease in GEP between 1999 to 2000, and between 2000 and 2001 study seasons was observed at the cutover site. Furthermore, the cutover site displayed a statistically significant ($P < 0.05$) 212 % increase in seasonal average production between 2001 and 2002.

Similarly, cutover site herbaceous vegetation had large fluctuations in seasonal average respiration during all study seasons, with fluxes ranging from -6.23 ± 2.19 in 2001 to -9.10 ± 11.20 in 1999. For example, there was a significant decrease ($P < 0.05$) in herbaceous respiration between 1999 and 2000, leading to a ~50% decline in fluxes. In contrast, there was no significant change in seasonal mean cutover site respiration from herbaceous vegetation between the 2000 and 2001 study seasons, with seasonal mean fluxes of $-9.38 \pm 3.60 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ and $-6.23 \pm 2.19 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ respectively. However, there was a significant increase ($P < 0.05$) in average seasonal herbaceous respiration between 2001 and 2002, relating to a ~135% increase.

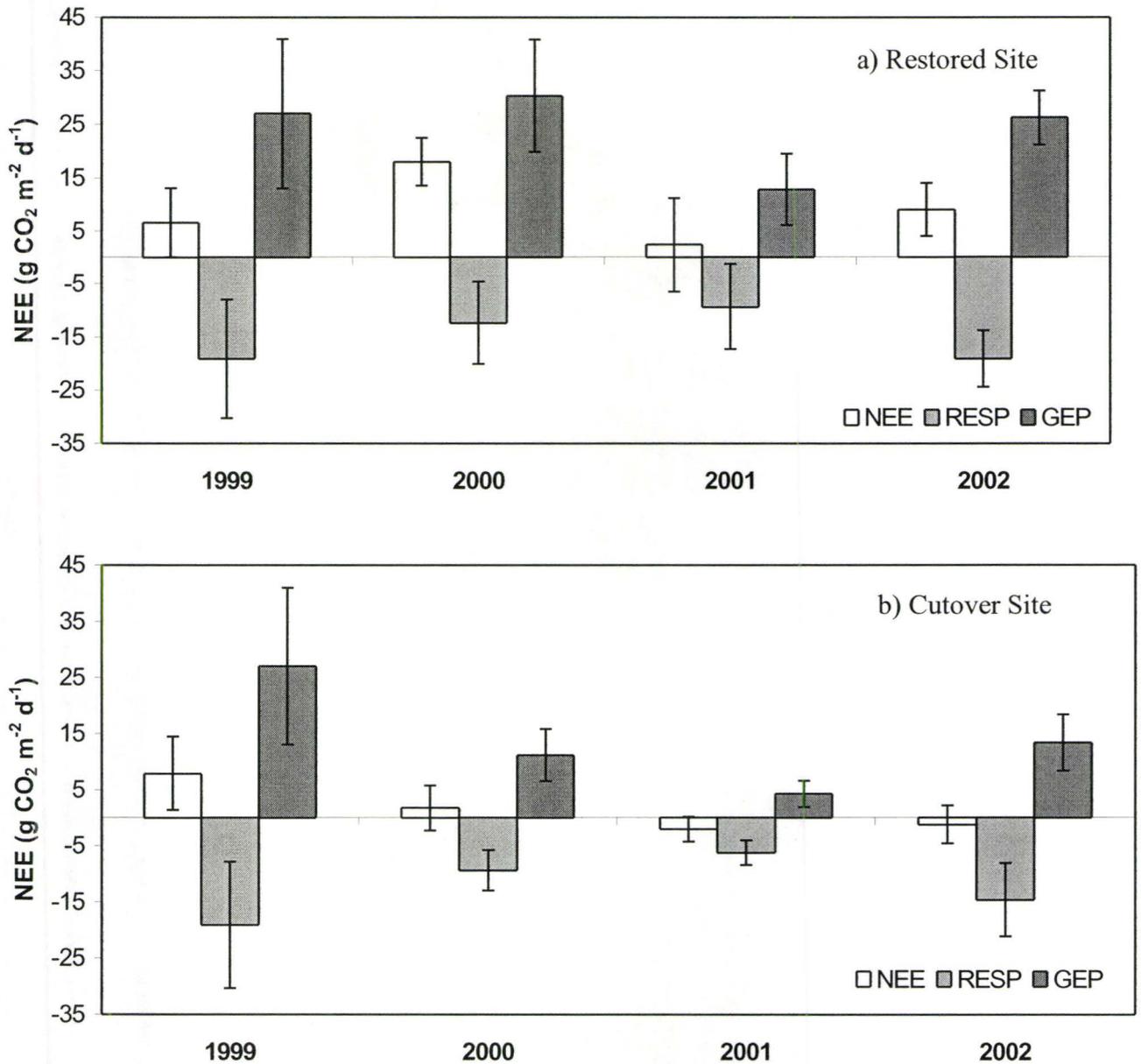


Figure 6.4: Seasonal average herbaceous vegetation net ecosystem exchange (NEE) (white bars), respiration (grey bars) and gross ecosystem production (GEP) (dark bars) at the a) restored and b) cutover sites from 1999-2002.

In general, ratios of gross ecosystem production (GEP) to respiration for moss and herbaceous vegetation were dominated by productivity at the restored site and dominated by respiration at the cutover site (Figure 6.5). Specifically, at the restored site, ratios for herbaceous vegetation were dominated by production in all study seasons, ranging from 1.38 in 2001 to 2.46 in 2000. Likewise, moss vegetation at the restored site were also dominated by production in all study seasons, with the exception of 1999, with ratios ranging from 0.78 in 1999 to 1.74 in 2001. In contrast, the ratios of cutover site moss production to respiration are 0.79 and 0.80 for the 1999 and 2000 study seasons respectively. However, only during 1999 and 2000 for herbaceous vegetation and 2001 study season for moss vegetation were average production estimates greater than respiration fluxes (Figure 6.5).

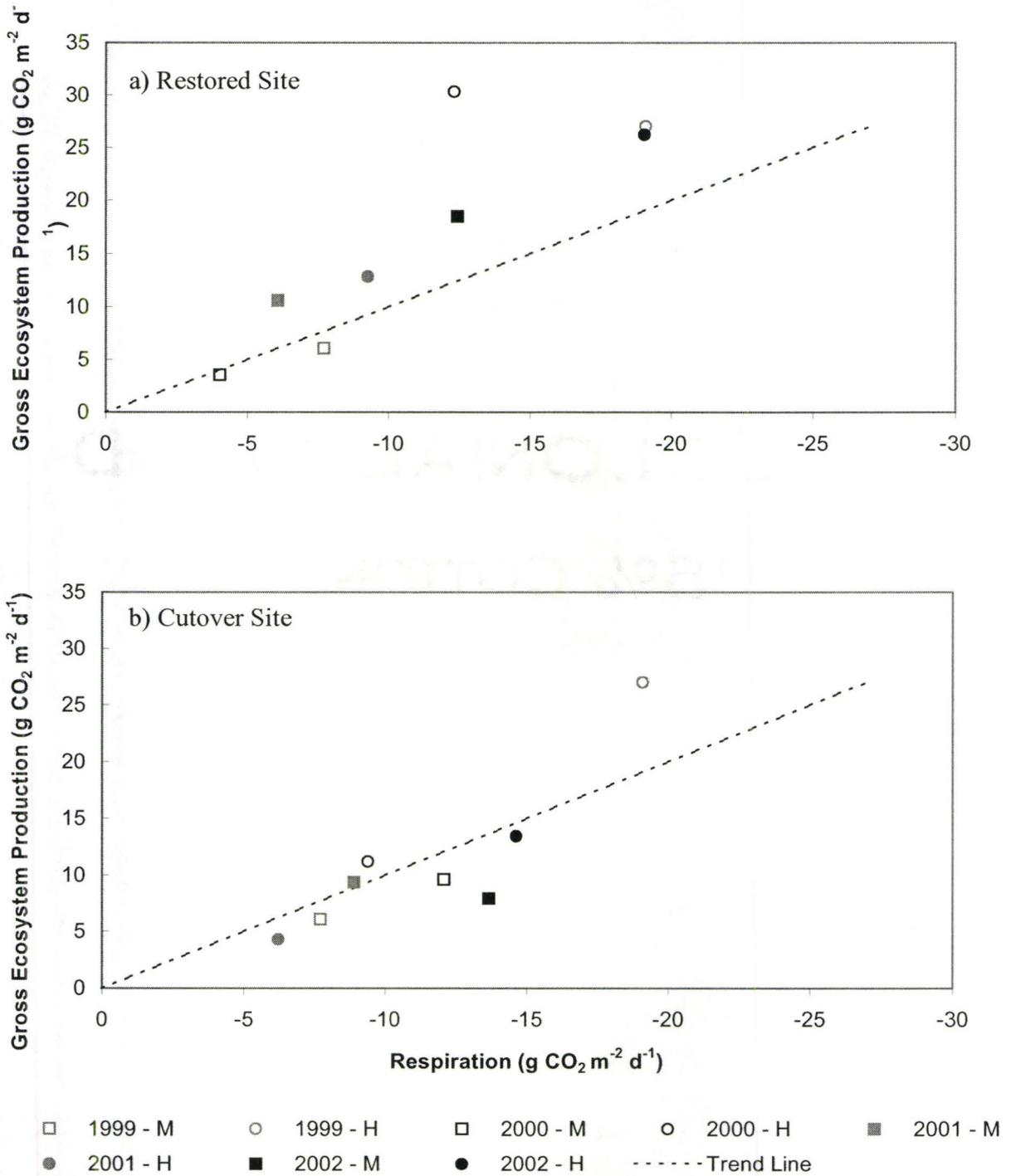


Figure 6.5: Ratio of gross ecosystem production versus respiration for both moss (M) (square) and herbaceous (H) (circle) vegetation at both the a) restored and b) cutover sites for 1999-2002.

6.2.3 Light Response Curves

Light response curves showing the relationship between gross ecosystem production (GEP) and photosynthetically active radiation (PAR) indicate that both the apparent quantum efficiency (ϕ) and the maximum GEP (A_{\max}) increased with time post-restoration (Figures 6.6 and 6.7) For example, restored site moss A_{\max} ranged from 7.87 g CO₂ m⁻² d⁻¹ in 2000, only one year post-restoration, to 35.5 g CO₂ m⁻² d⁻¹ in 2002 (Table 6.1). Whereas, herbaceous vegetation A_{\max} ranged from 17.3 g CO₂ m⁻² d⁻¹ in 2001 to 43.2 g CO₂ m⁻² d⁻¹ in 2000. For both moss and herbaceous vegetation, cutover site A_{\max} is significantly lower compared to the restored site in each study season. For example, average moss A_{\max} for the cutover site ranged from 11.1 g CO₂ m⁻² d⁻¹ in 2000 to 19.7 g CO₂ m⁻² d⁻¹ in 2001 (Table 6.1). As well, changes in the initial slope of the light response curve (ϕ) which indicates the rate of GEP increase at low light levels have also increased with time post-restoration. Restored site moss slope values ranged from 0.03 in 2000 to 0.05 in 2002 (Table 6.1). However, the restored site herbaceous vegetation had much steeper initial slopes compared to the moss locations with a range of 0.08 in 2001 to 0.13 in 2000 (Table 6.1). Furthermore, the initial slope estimates for the cutover site are smaller as compared to estimates for both moss and herbaceous locations from the restored site.

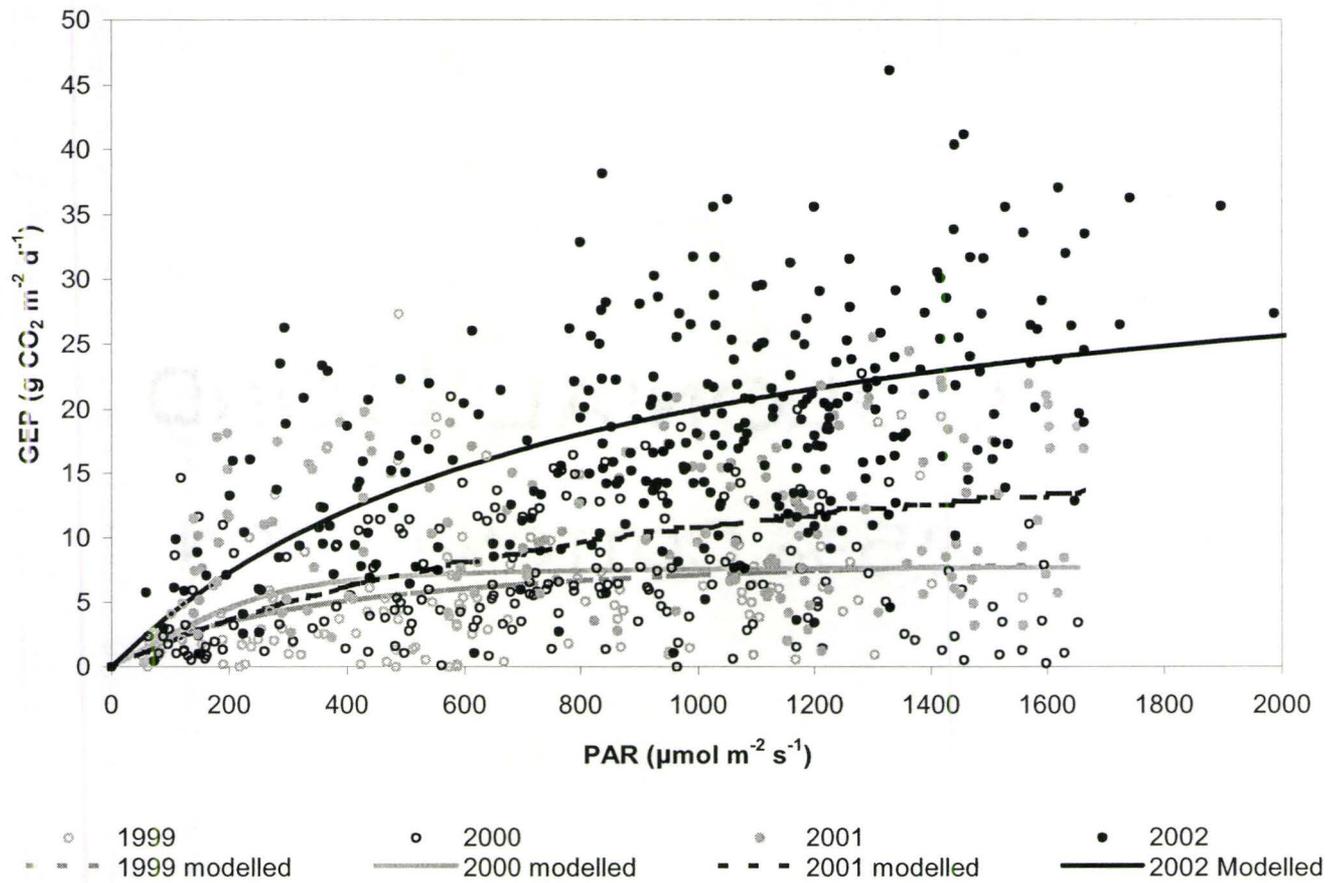


Figure 6.6: Restored site moss gross ecosystem production (GEP) versus photosynthetically active radiation (PAR) for 1999-2002.

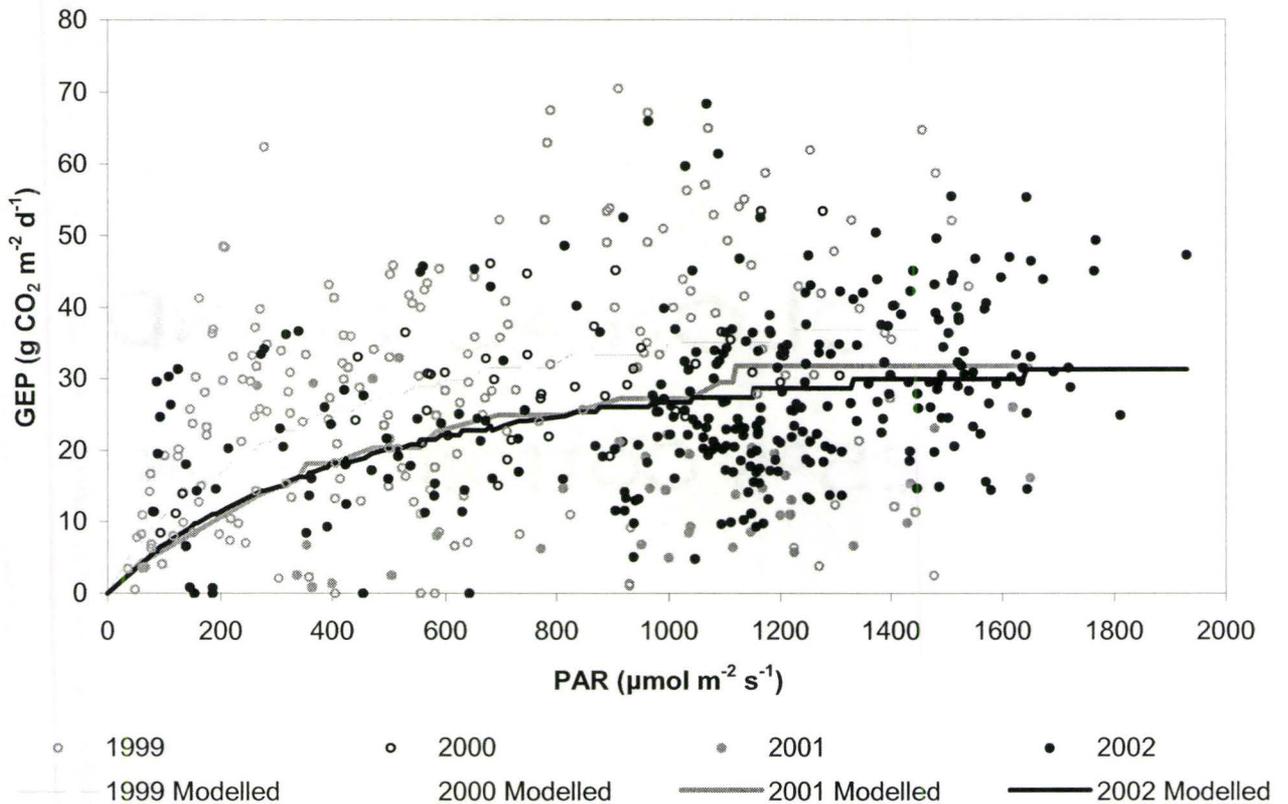


Figure 6.7: Restored site herbaceous gross ecosystem production (GEP) versus photosynthetically active radiation (PAR) for 1999-2002. Note, y-axis scale is different that in Figure 6.6.

Table 6.1: GEP modelling parameters for moss and herbaceous vegetation at both the a) restored and b) cutover sites for 1999-2002.

		GEP Modelling Parameters							
		Mosses				Herbaceous			
Site	Year	n	ϕ	Amax	k	n	ϕ	Amax	k
a) Restored	1999	199	0.0276	9.63	1.13×10^{-8}	203	0.14	45.4	8.11×10^{-15}
	2000	182	0.0259	7.87	0.9062	44	0.133	43.2	1.84×10^{-4}
	2001	149	0.0324	18.7	2.54×10^{-15}	43	0.0772	17.3	1.77×10^{-15}
	2002	296	0.0459	35.5	0.0459	288	0.0806	40	1.09×10^{-14}
b) Cutover	1999	199	0.0276	9.63	1.13×10^{-8}	203	0.14	45.4	8.11×10^{-15}
	2000	84	0.0125	11.1	0.993	84	0.0137	30.1	9.24×10^{-5}
	2001	88	0.0208	19.7	1.12×10^{-4}	84	0.0162	6.84	3.73×10^{-8}
	2002	134	0.111	10.5	1	164	0.0522	20.2	2.8×10^{-15}

6.3 Discussion

6.3.1 Changes in Moss Net Ecosystem Exchange Post-Restoration

Prior to restoration, moss vegetation was a net seasonal source of CO₂ to the atmosphere, with respiration dominating the overall net exchange. The net release of CO₂ to the atmosphere pre-restoration was due to the poor hydrological conditions present at the cutover site with significantly high soil water tensions and reduced soil moisture (Shantz, 2003). As well, the 1999 study season was warmer than the 30-year mean, having the potential to increase microbial activity. Pre-restoration, *Sphagnum* moss was not present at either the cutover or restored sites, where all moss vegetation was *Polytrichum strictum*, a pioneer species that has the ability to grow abundantly on cutover sites (Groeneveld and Rochefort, 2005). These species have a high tolerance to desiccation and as such become a nursing species aiding the recovery of *Sphagnum* moss species (Groeneveld and Rochefort, 2005).

Post-restoration, the restored site moss seasonal NEE significantly increased, with an overall increase by ~220% in only three years post restoration, increasing the net CO₂ sink function at these sites. The restored site had a positive NEE in 2001 and 2002, with production greater than respiration at these sites, creating a seasonal net sink two and three years post-restoration for moss vegetation. This increase in NEE is dominated by a significant increase in productivity post-restoration, with a ~200% increase between 2000 and 2001 and a ~75% increase from 2001 to 2002. These estimates of productivity are dependent on climatic variability, namely precipitation and air temperature as well as the supply of nutrients in addition to the composition of the species present (Rochefort et al.,

1990). Specifically, the increased productivity with time post-restoration can be attributed to substantial improvements in hydrological conditions necessary for moss establishment due to active rewetting in the restoration process. Where the restoration process maintained soil moisture above 50% and soil-water pressures above -100 mb, required for adequate *Sphagnum* growth despite limited precipitation three years post-restoration (Shantz, 2003).

The results presented in this study for seasonal average GEP for moss vegetation at the restored site are significantly greater than previous studies on restored peatlands. A study conducted by Waddington et al. (2003b) determined that mean daily GEP at a natural site ($2.6 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$) was significantly lower than a restored plot ($5.1 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$). However, the restored site had increased seasonal losses of CO_2 as compared to the natural site as a result of respiration dominating the net exchange at the restored site. Whereas, seasonal average moss GEP at the restored site in this study ranged from $6.07 \pm 5.25 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ in 1999 to $18.50 \pm 6.01 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ in 2000, however, both the 1999 and 2000 study seasons were also a net source of CO_2 to the atmosphere. Furthermore, McNeil and Waddington (2003), found that *Sphagnum* moss vegetation at a naturally revegetated block-cut restored peatland was a seasonal source of atmospheric CO_2 of -57.5 g C m^{-2} due to large respiration fluxes. Seasonal moss species respiration at the restored site increased significantly between the 2001 and 2002 study seasons. This increase in respiration can be attributed to climatic variability, as 2002 was a dry year as compared to all other previous study seasons as well as the long-term average. Moreover, the increase in seasonal moss respiration with time post restoration can also be related to

a “priming effect” (Kuzyakov et al., 2000 and 2001), where the accumulation of both above and belowground biomass ultimately becomes a source of labile carbon for microbial activity during senescence and by the excretion of root exudates (Marinier et al., 2004).

At the restored site, there was also a shift in the dominance of moss species present over time with a 22% increase in *Sphagnum* moss cover between 1999-2001, where the site contained no *Sphagnum* cover prior to restoration (Zhou et al., 2005). As such, the goal of restoration to return a functional peatland ecosystem that is both a net carbon sink as well as having an established *Sphagnum* layer is being met. It is expected that *Sphagnum* moss will eventually replace all *Polytrichum strictum* moss as they are adapted to poor nutrient conditions, through their characteristic slow growth rates and increased root to shoot ratios (Bridgham et al., 1998). As such, *Sphagnum* mosses can out compete any other species present (van Breeman, 1995) by their ability to modify their environment by creating harsh, acidic surroundings. As *Sphagnum* continues to colonize the restored site, a new self-regulating acrotelm (McNeil and Waddington, 2003) will develop to help maintain higher soil moisture conditions. This will subsequently aid in the removal of *Polytrichum strictum* cover, as it generally colonizes drier locations (Groeneveld and Rochefort, 2005). Moreover, a *Sphagnum* moss cover that regains the net carbon function similar to natural peatlands is essential for achieving successful restoration.

In contrast, the cutover site displayed negative NEE fluxes dominated by respiration that were not statistically significantly different in all years studied. As well, the cutover

site moss vegetation contained no *Sphagnum* moss and was dominated by *Polytrichum strictum* as it can colonize such harsh conditions (Groeneveld and Rochefort, 2005) present post-abandonment. Shantz (2003) determined that the hydrological conditions present at the cutover site were inadequate to support the moisture thresholds necessary for moss establishment. Moreover, there was large interannual variability in moss respiration at the cutover site, with a 57% increase between 1999 and 2000 and a 54% increase between 2001 and 2002. These variations in respiratory fluxes are likely related to climatic variations, for example, the 2002 study season had near drought like conditions, which increases the aerobic zone allowing for increased oxidation as well as increased diffusive transport of CO₂ to the atmosphere. Previous studies have also found large interannual variability in net ecosystem exchange where bogs can shift from a sink to a source of CO₂ during a drought year (Alm et al., 1999). Similarly, Bubier et al. (2003b) concluded that under drier conditions, rates of NEE declined as a result of increasing rates of respiration as opposed to a decrease in productivity.

The restored site moss NEE was dominated by production in all study seasons, with the exception of 1999, with ratios of production to respiration ranging from 0.78 in 1999 to 1.74 in 2001. Alternatively, cutover site ratios for moss vegetation were heavily dominated by respiration rather than production. For example, the ratios of cutover site moss production to respiration were 0.79 and 0.80 for the 1999 and 2000 study seasons respectively.

Therefore, restoration has produced significant changes in seasonal moss NEE due to active restoration and rewetting by creating increased productivity of mosses at the

restored site as compared to the cutover site where hydrological conditions are unsuitable for prolific moss growth (Shantz, 2003). As well, the percent cover of moss vegetation, namely *Sphagnum* spp., are increasing with time post-restoration. This shift towards *Sphagnum* species will eventually out compete pioneer species such as *Polytrichum strictum* (Groeneveld and Rochefort, 2005) and is a desirable goal of peatland restoration (Rochefort et al., 2003).

6.3.2 Changes in Herbaceous Net Ecosystem Exchange Post-Restoration

Herbaceous vegetation displayed larger variability in net ecosystem exchange of CO₂ with time post-restoration. Similar to moss vegetation, the restored site had a positive NEE in all years post-restoration and therefore represents a net seasonal net uptake of atmospheric CO₂. Specifically, seasonal mean herbaceous NEE increased by 14% from pre to three years post-restoration. There was a statistically significant ($P < 0.05$) increase in NEE from 1999 to 2000 ultimately resulting in a ~130% increase in CO₂ storage capacity pre to one year post-restoration. Even though, there was a statistically significant ($p < 0.05$) drop in the NEE from 2000 to 2001 the net exchange still remained positive. Previous studies conducted in European restored peatlands show similar increases in net CO₂ uptake with time post-restoration, generally as a result of increased herbaceous vegetation cover. A study conducted by Tuittila et al. (1999), found that active rewetting decreased respiration as well as increasing productivity at the site, specifically from *Eriophorum* spp. This study determined that the site becomes a net sink of atmospheric CO₂ (9.1 g CO₂-C m⁻²) from a dense *Eriophorum* cover after only two years post-restoration. Similarly, Komulainen et al. (1999), found that rewetting drained peatlands

increased *Eriophorum* spp. cover and ultimately changed the seasonal carbon balance towards an increase in CO₂ sequestration, where the seasonal CO₂ balance ranged between 54-101 g C m⁻² at the rewetted site.

For the restored site in this study, productivity remained fairly high during all study seasons ranging from 12.82 ± 6.73 g CO₂ m⁻² d⁻¹ in 2001 to 30.34 ± 10.53 g CO₂ m⁻² d⁻¹ during 2000. Additionally, there was significant ($P < 0.05$) increase in the production from the seasonal average minimum 2001 flux to 26.22 ± 5.03 g CO₂ m⁻² d⁻¹ in 2002, resulting in an 105% increase over two study seasons.

As for herbaceous respiration at the restored site there was a significant decrease of 35% between pre (1999) and one-year post restoration (2000). This decrease in respiration one year post-restoration could be due to active rewetting at the restored site by both a reduction in aerobic decomposition in addition to a reduced rate of diffusion of CO₂ to the atmosphere (Jackson, 1985). Furthermore, there was a significant ($P < 0.05$) increase in respiration during the 2002 study season, by ~105 % from 2001. This significant increase at the restored site three years post restoration can be attributed to increased biomass accumulation with time post-restoration creating a labile carbon source with the potential to increased peat respiration (Marinier et al., 2004). Furthermore, it is suggested that root respiration can be attributed to 35-45% of the total peat respiration in sites with abundant vegetation growth (Silvola et al., 1996). This increase in root respiration can also lead to an increase in labile carbon sources for microbes from root exudates (Joabsson, 2001).

In contrast, cutover site herbaceous vegetation represented a net release of CO₂, during both the 2001 and 2002 study seasons, with seasonal average fluxes of -9.38 ± 3.60 g CO₂ m⁻² d⁻¹ and -6.23 ± 2.19 g CO₂ m⁻² d⁻¹ respectively. Again these negative NEE fluxes for herbaceous vegetation at the cutover site can be explained due to climatic variability, as 2002 was a dry and warm study season.

It is important to note that herbaceous species are not only important in storing CO₂ in newly restored peatlands, they also provide improved microclimatic conditions for other bog species, namely *Sphagnum* mosses to establish on these cutover sites (McNeil and Waddington, 2003). Herbaceous vegetation such as *Eriophorum vaginatum* establish rapidly after restoration and subsequently its colonization improves the microhabitat for the initiation and growth of other vascular plants and mosses (Lavoie et al., 2003). Unfortunately, Day (2003) determined that herbaceous vegetation increased the rates of CH₄ emissions in restored peatlands by a combination of providing a conduit for CH₄ to escape to the atmosphere without oxidation as well as providing an additional source of labile carbon for microbial activity from root exudates. Consequently, herbaceous species represent a net seasonal uptake of CO₂ post-restoration at Bois-des-Bel, at the same time as providing adequate conditions for moss establishment. However, they also represent a net source of CH₄ post-restoration (Day, 2003), which has larger implications in the net carbon sink function of restored peatland ecosystems, since it has a global warming potential 21 times greater than CO₂.

However, when the seasonal average net ecosystem exchange of CO₂ for both moss and herbaceous vegetation are compared, it is evident that there is heterogeneity and

variability in NEE for different vegetation types. As a result, the individual vegetation communities respond differently to ecosystem restoration, as some communities acting as sources and some as sinks of atmospheric CO₂ (Bubier et al., 1998), mainly as a result of differential physiological responses to moisture. Overall, *Sphagnum* mosses have a much lower photosynthetic rate compared to herbaceous vegetation, likely because transpiration by vascular plants in wetlands rarely experience soil moisture conditions low enough to inhibit growth (Griffis et al., 2000).

6.3.3 *Changes Light Response of Production Post-Restoration*

It is generally accepted that the dominant environmental control on gross ecosystem production (GEP) is photosynthetically active radiation (PAR) (Bubier et al., 1998). As a result, seasonal production is often modelled as a rectangular hyperbolic relationship between GEP and PAR (Frolking et al., 1998) (light response curves). However, this relationship can be complicated by a number of factors including: vegetation temperature, soil and vegetation potential, atmospheric moisture deficit, internal and ambient CO₂ concentrations and nutrient status. Specifically, results post-restoration at Bois-des-Bel suggest that both moss and herbaceous vegetation exhibit significantly improved net CO₂ fixation. Specifically, light response curves for both moss and herbaceous vegetation at the restored site indicate that both the apparent quantum efficiency (ϕ) and the maximum GEP (A_{\max}) have increased with time post-restoration. For both moss and herbaceous vegetation, cutover site A_{\max} is significantly lower compared to the restored site in each study season. The range in A_{\max} observed at Bois-des-Bel, post-restoration are

significantly greater than estimates made from previous studies in natural peatlands. Specifically, Frohking et al., (1998) modelled GEP and PAR using a rectangular hyperbola from a range of northern boreal peatland types, where A_{\max} for bogs studied ranged from 4.1 ± 0.09 to 7.1 ± 0.47 . A study conducted by Campeau and Rochefort (2000), also found a deviation between growth rates of mosses (*Sphagnum*) at both natural and restored peatlands. They suggested that in restored sites, *Sphagnum* mosses had a greater density and number of capitula present as compared to natural peatlands, which ultimately allows the developing *Sphagnum* species to maintain a higher moisture content as well as increasing productivity (Campeau and Rochefort, 2000). Furthermore, there is also increased scatter in light response curves with time post-restoration, meaning that these relationships are confounded by the continually emerging heterogeneous vegetation cover.

Moreover, the rate of GEP increases at low light levels (initial slope of the light response curve (ϕ)) has also increased with time post-restoration. Initial slope estimates for restored site moss vegetation ranged from 0.03 in 2000 to 0.05 in 2002. Again, these estimates are much greater as compared to average curve fitting parameters for natural peatlands. Frohking et al., (1998) calculated an average midseason-modelled initial slope of 0.017 ± 0.001 . In addition, the restored site herbaceous vegetation had much steeper initial slopes compared to the moss vegetation with a range of 0.08 in 2001 to 0.13 in 2000. Furthermore, the initial slope estimates for the cutover site are smaller as compared to estimates for both moss and herbaceous locations from the restored site.

6.3.4 *Implications for Restoration*

The major goals of peatland restoration are to re-establish a fully vegetated site dominated by *Sphagnum* moss species as well as a return to natural net carbon sink function at the sites (Rocheport et al., 2003). Ultimately the rate at which peatlands will return to a net carbon sink will depend on the rate of production and decomposition at these sites. As such it is important to know these rates in restored peatlands in order to effectively evaluate the success of the restoration approach. In general, natural peatland ecosystems act as long-term sinks of atmospheric CO₂ (Gorham, 1991), however, numerous studies have shown significant interannual variability in the source/sink strength of peatlands (Bubier et al., 2003a; Griffis et al., 2000) mainly as a result of climatic variability. Results from this study indicate that active ecosystem scale restoration techniques conducted at Bois-des-Bel have the potential to return the system to a seasonal net sink of atmospheric CO₂ within three years post-restoration. The resultant seasonal increase in CO₂ accumulation post-restoration can be attributed in part by a reduction in peat respiration via active rewetting, in addition to the significant increase in ecosystem productivity from an evolving vegetative cover. Specifically active restoration significantly increased seasonal moss NEE by ~220% from 1999 to 2002, in only three years post restoration, thus increasing net CO₂ sink function at these sites. In contrast, the cutover site displayed negative NEE fluxes dominated by respiration that are not statistically significantly different in all years studied each other. Therefore ecosystem scale active restoration increased the net seasonal CO₂ uptake for both herbaceous and moss species after only three years post-restoration, where as vegetation

at the cutover site still remains a net seasonal source of CO₂ to the atmosphere 25 years post-abandonment. However, it should be noted that these flux estimates only consider the main growing season, and without the incorporation of winter flux estimates, these results could potentially be overestimated as winter CO₂ losses from peatlands can attribute to as much as 21% of annual release (Alm et al, 2002).

Furthermore, the importance of companion species, namely herbaceous (*Eriophorum* spp.) and *Polytrichum strictum* on the growth and establishment of *Sphagnum* mosses in restored cutover peatlands needs to be fully understood as a continuous *Sphagnum* moss layer is the ultimate goal of peatland restoration as it recreates a peat-accumulating ecosystem.

CHAPTER 7: ECOSYSTEM SCALED NET ECOSYSTEM EXCHANGE ESTIMATES IN A CUTOVER AND RECENTLY RESTORED PEATLAND

7.1 Introduction

Previous studies conducted in order to determine the ecosystem scale net ecosystem exchange of a recently restored peatland have show significant increase in the flux of CO₂ to the atmosphere post-restoration. For example, a study using the eddy covariance micrometeorological technique at the Bois-des-Bel peatland (Petrone et al., 2003) has shown a significant increase in carbon dioxide fluxes to the atmosphere three years post-restoration. The net ecosystem exchange post-restoration was approximately double the rates of CO₂ fluxes prior to active restoration. The first and second year post-restoration seasonal NEE averages were ~480 g C m⁻² and ~470 g C m⁻² respectively. This increase in flux post-restoration was suggested to occur as a result of the lack of a carbon fixing vegetative surface resulting in limited production and highly variable moisture conditions that may have increased CO₂ decomposition in addition to decomposing straw mulch present on the site. However, simulated NEE exchange estimates based on these initial eddy covariance micrometeorological measurements indicate that the site has the potential to return to a net carbon sink by the end of the sixth year post-restoration (Petrone, 2002) by increased CO₂ uptake by the surface vegetation. Furthermore, chamber based net ecosystem exchange estimates from this study (Chapters 5 and 6) indicate that active ecosystem scale restoration techniques conducted at Bois-des-Bel have the potential to return the system to a seasonal net sink of atmospheric CO₂ within three years post-restoration, due in part by increased production with time post-

restoration from both an emerging herbaceous and moss vegetation cover, as well as a reduction in peat respiration due to active rewetting. Therefore, the objective of this chapter is to use empirical relationships based on the dominant controls governing CO₂ exchange in restored peatland ecosystems, to upscale chamber based net ecosystem exchange to the ecosystem scale in order to estimate when the site will be fully “restored” from a carbon sequestration perspective.

7.2 Results

7.2.1 Modelling Parameters

Each growing season was divided into three periods: Period 1 (“pre-green”) from May 17 to June 8, Period 2 (“green”) from June 19 to September 2, and lastly, Period 3 (“post-green”) from September 2 to October 11 (Petroni et al., 2003). These periods corresponded to initial development, summer growth and senescence (Petroni et al., 2003). It should be noted that during the 2002 study season flux measurements were only made during the first two periods (“pre-green” and “green”).

GEP for each vegetation type over each of the three study periods for both the restored and cutover sites pre (1999) and post-restoration (2000-2002) were modelled as a rectangular hyperbolic function of PAR. Root mean square error (RMSE) analysis of seasonally averaged modelled GEP fluxes and period based modelled GEP fluxes compared to field based chamber fluxes (Table 7.1), indicate that the period based GEP estimates on average had lower RMSE compared to seasonal average GEP estimates. Consequently, period based estimates were used to upscale chamber GEP.

Empirical relationships of chamber-based measurements of respiration were determined from linear regression analysis with environmental variables of peat temperature at 2, 5 and 10 cm depths and volumetric soil water content (VWC%). Continuously modelled respiration fluxes were calculated based on the empirical relationships with the best R^2 value for each of the three periods in for each collar and with continuously recorded measurements of peat temperature and soil moisture. Similar to GEP modelled fluxes, period-based modelled respiration fluxes displayed smaller RMSE values when compared to seasonally modelled relationships (Table 7.2) and thus were used to upscale chamber respiration values to the ecosystem level.

Table 7.1: Root mean square error (RMSE) for daily average chamber GEP as compared to modelled GEP at both the a) cutover b) and restored sites for 1999-2002.

	a) Cutover Site						b) Restored Site			
	Moss		Herbaceous		Shrub		Moss		Herbaceous	
	<i>Seas.</i>	<i>Periods.</i>	<i>Seas.</i>	<i>Periods.</i>	<i>Seas.</i>	<i>Periods.</i>	<i>Seas.</i>	<i>Periods.</i>	<i>Seas.</i>	<i>Periods.</i>
1999	5.20*	5.55*	18.43*	20.71*	N/a	N/a	5.20	5.55	18.43	20.71
2000	7.20	6.47	7.20	6.47	9.61	9.78	6.57	6.57	32.63	20.31
2001	6.75	6.51	3.01	3.14	6.44	6.32	5.58	4.79	11.33	7.38
2002	4.23	4.61	7.81	7.05	N/a	N/a	9.72	9.48	13.49	12.85

*Note: Fluxes of *Polytrichum* and *Eriophorum* were only made from the site now known as the “restored” site in 1999. However, these fluxes were assumed to be the same as fluxes that would have been measured at the “cutover” site as no active restoration had taken place.

Table 7.2: Root mean square error (RMSE) for daily average chamber respiration as compared to modelled respiration for the a) cutover and b) restored sites.

	a) Cutover Site									
	Moss		Herbaceous		Shrub		Peat		Ditch	
	<i>Seas.</i>	<i>Periods.</i>	<i>Seas.</i>	<i>Periods.</i>	<i>Seas.</i>	<i>Periods.</i>	<i>Seas.</i>	<i>Periods.</i>	<i>Seas.</i>	<i>Periods.</i>
1999	3.69*	3.39*	13.53*	8.58*	N/a	N/a	3.69	3.39	13.53	8.58
2000	4.85	6.97	3.81	3.87	5.03	4.98	1.00	0.94	4.07	3.91
2001	3.07	4.05	2.58	2.24	3.51	3.46	1.79	1.98	2.53	3.21
2002	3.99	4.62	3.99	3.79	N/a	N/a	N/a	N/a	N/a	N/a

*Note: Fluxes of *Polytrichum* and *Eriophorum* were only made from the site now known as the “restored” site in 1999. However, these fluxes were assumed to be the same as fluxes that would have been measured at the “cutover” site as no active restoration had taken place.

	b) Restored Site							
	Moss		Herbaceous		Peat		Ditch	
	<i>Seas.</i>	<i>Periods.</i>	<i>Seas.</i>	<i>Periods.</i>	<i>Seas.</i>	<i>Periods.</i>	<i>Seas.</i>	<i>Periods.</i>
1999	3.57	3.80	6.67	6.97	3.20	1.79	9.46	5.51
2000	1.83	1.78	5.49	5.16	1.33	1.27	3.07	3.09
2001	3.20	3.31	8.68	9.00	2.09	1.85	2.66	3.15
2002	4.39	5.38	6.80	8.74	N/a	N/a	N/a	N/a

7.2.2 Chamber Modelled Net Ecosystem Exchange of CO₂

Total seasonal estimates of net ecosystem exchange (NEE) of CO₂ were determined as the difference between chamber-based continuously modelled GEP and respiration estimates previously discussed and aggregated over the three periods of each study season. Total seasonal NEE was determined both pre (1999) and two years post-restoration (2000 and 2001) for each individual surface element including: peat, ditches, mosses, herbaceous vegetation and for the cutover site, shrubs.

These NEE totals were calculated based on the aggregated average seasonal fluxes, the number of days of each study season and finally the percent cover of each component. The total NEE fluxes calculated for the restored site show dramatic changes in the source-sink capacity of the site with time post-restoration (Figure 7.1). Pre-restoration (1999), all surface elements sampled at the restored site displayed a net release of CO₂ to the atmosphere. The largest releases in the 1999 season were from vascular vegetation and ditches with net releases of $-399.0 \text{ g C m}^{-2}$ and $-352.8 \text{ g C m}^{-2}$ respectively. However, two years post-restoration, the restored site had a significant increase in the amount of carbon stored by the surface elements compared to pre-restoration conditions. Specifically, the peat and ditch surface components still displayed a net release of CO₂ to the atmosphere of -79.5 g C m^{-2} and $-112.0 \text{ g C m}^{-2}$ for the 2000 and -73.7 g C m^{-2} and $-144.2 \text{ g C m}^{-2}$ for the 2001 study seasons. However, both herbaceous and moss vegetation at the restored site shift from a large source of CO₂ pre-restoration to an increased net sink with time post restoration. For example, restored site moss vegetation increases its CO₂ sink strength from 12.3 g C m^{-2} in 2000 to 67.2 g C m^{-2} in 2001. At both pre and

post-restoration all surface elements at the cutover site, whether peat, ditch or vegetation were all net sources of CO₂ to the atmosphere, which is to be expected as site conditions had not been actively restored. However, similar to the restored site NEE totals, there was a decreasing trend in the net release of CO₂ to the atmosphere from the cutover site from 1999 to 2001. This decreasing trend was estimated to be a function of interannual climatic variability driving the NEE CO₂ flux at this site.

By weighting the seasonal NEE for each community by the percent surface cover of each surface elements the interannual variability in growing season NEE at the peatland scale can be estimated (Figure 7.2). For the restored site, it is apparent that the area weighted, upscaled chamber NEE fluxes show a much larger source of CO₂ to the atmosphere pre-restoration (1999) compared to post-restoration. It is also evident that the site is a net sink of CO₂ to the atmosphere on a number of days during the three years post-restoration (2000-2002) in response to active rewetting and an increased vegetation cover. Seasonal NEE estimates from the 2002 study season were included for periods one and two and were upscaled based on bare peat and ditch respiration estimates made during the 2001 study season, as these surface elements were not measured during the 2002 study season. In contrast, the cutover site upscaled modelled NEE fluxes show much less interannual variability between pre and post-restoration, as would be expected due to lack of active manipulation of this site. As well, during the “green” period, there are no days where a positive NEE is achieved, meaning that on most days over the study period, the cutover site is a net source of CO₂ to the atmosphere (Figure 7.2)

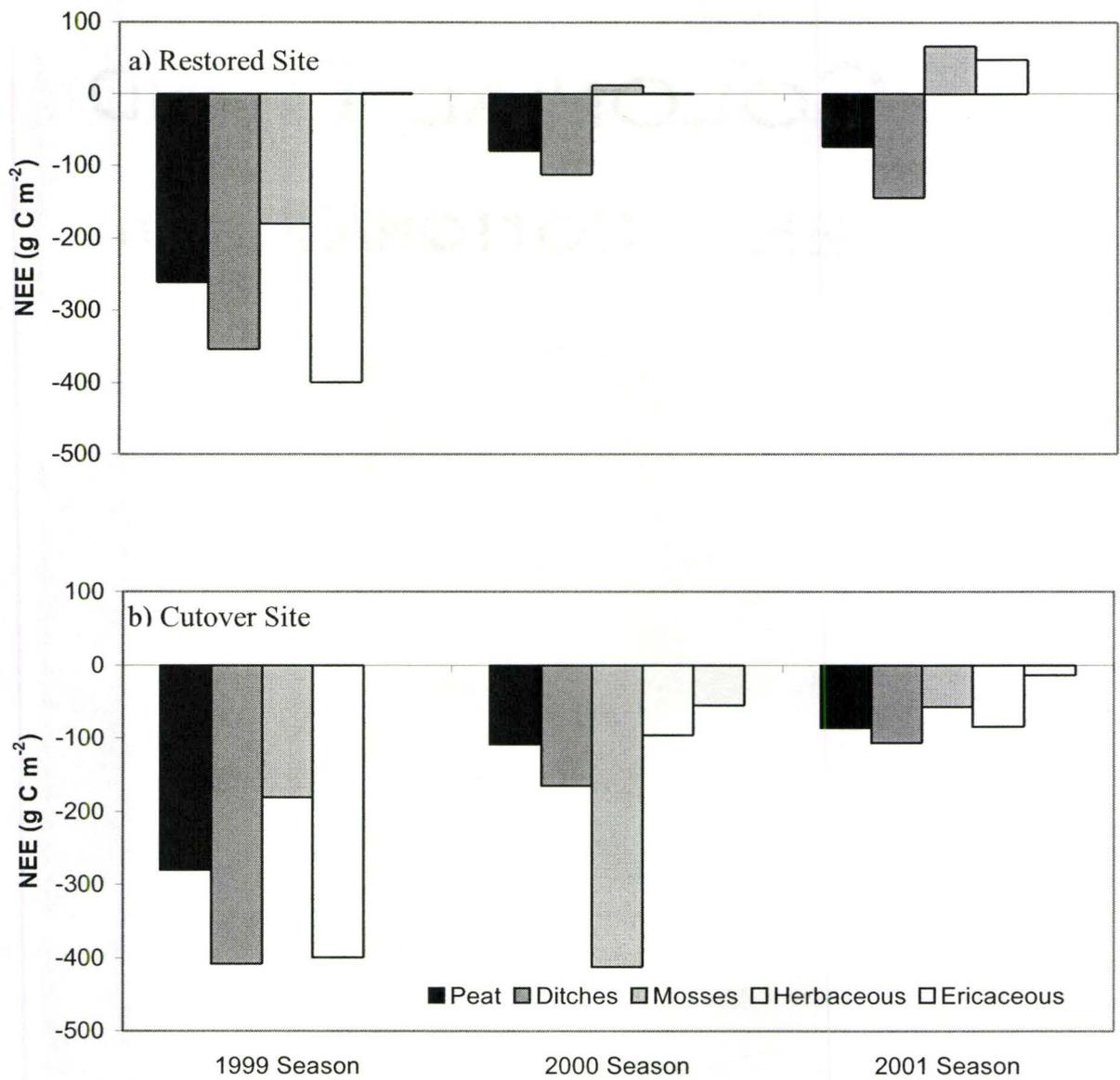


Figure 7.1: Seasonal modelled total NEE at both the a) restored and b) cutover sites for 1999-2002.

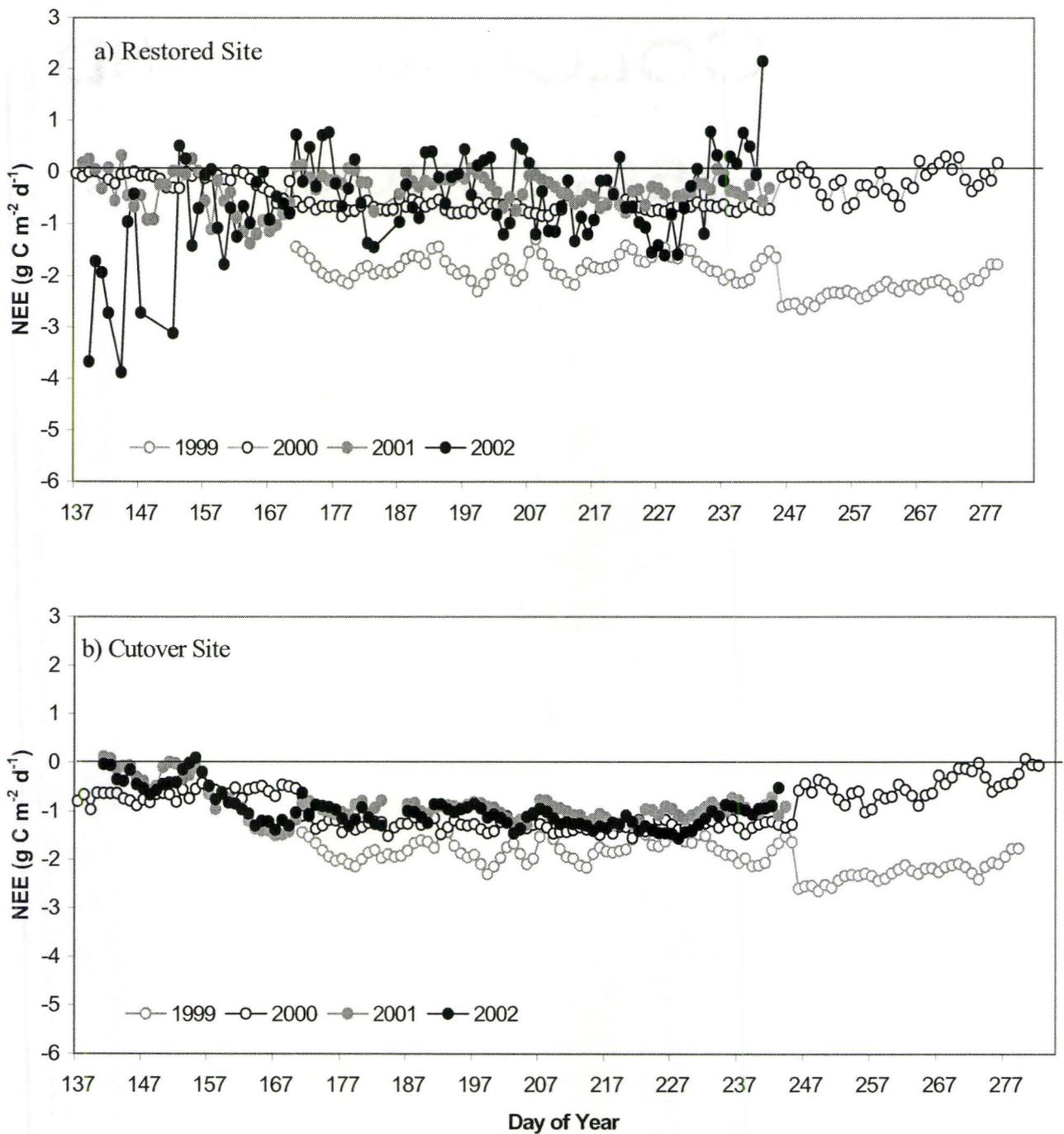


Figure 7.2: Interannual area weighted modelled NEE at both the a) restored and b) cutover sites for 1999 (open grey), 2000 (open black), 2001 (grey) and 2002 (black).

When comparing the seasonal totals of NEE for both the restored and cutover sites as determined by upscaled chamber estimates, the restored site show the site is a small sink of CO₂ during the 2000 study season (13.0 g C m⁻²) and a slightly larger sink during the 2001 season (20.2 g C m⁻²) (Figure 7.3). Again, it should be noted that the 2002 seasonal total NEE was not calculated as data was not collected during period three of that study season. However, to investigate interannual comparison, total NEE during the “green” period (period 2), was calculated for both pre and all years post-restoration (Figure 7.4). The green period (period two), represents the period of peak vegetative growth, especially for herbaceous species, which subsequently can lead to a period of maximum uptake of CO₂ for the restored site. Green period seasonal NEE estimates were upscaled based on the percent cover of all dominant surface elements for both the restored and cutover sites (Figure 7.4). Results show that the restored site increased its net carbon sink strength during the green period with time post-restoration, due to the substantial increase in vegetative cover and an overall reduction of bare peat. Specifically, the seasonal total NEE during the green period for the restored site ranged from a large source of CO₂ to the atmosphere prior to restoration (1999) (-134.75 g C m⁻²), to a seasonal net sink three years (2003) post-restoration (4.28 g C m⁻²). It should be noted that the estimated green period NEE for the 2002 study season incorporated 2001 flux estimates for both peat and ditch respiration as these surface elements were not sampled during the 2002 study season.

For the cutover site, green period total NEE prior to restoration was not significantly different from the restored site estimates, with a total seasonal flux of -130.92 g C m⁻².

However, the cutover site green period NEE significantly increased, towards enhanced carbon uptake between 1999 and 2000, with a reduction in source of CO₂ to the atmosphere by ~42 g C m⁻². Moreover, during the study seasons post-restoration the cutover site displayed no significant changes in green period NEE between 2000, 2001 and 2002 with all seasonal totals being a net source of CO₂ to the atmosphere of -89.21 g C m⁻², -65.95 g C m⁻² and -72.05 g C m⁻² respectively.

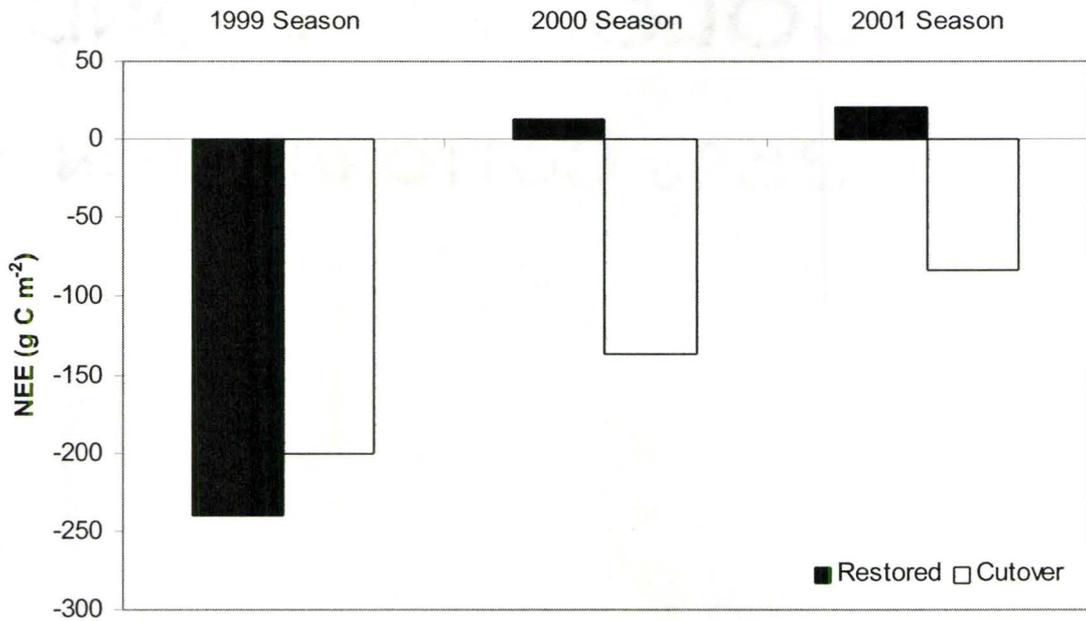


Figure 7.3: Chamber modelled total seasonal NEE for both the restored (dark bars) and cutover sites (white bars) for 1999-2001.

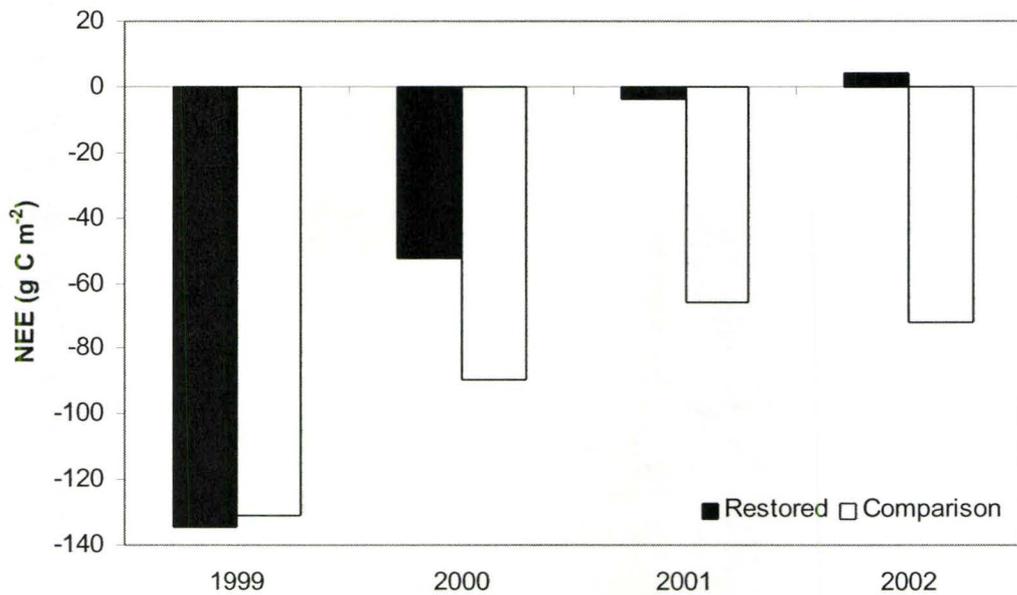


Figure 7.4: Period 2 (June 19 to September 2) NEE for both the restored (dark bars) and cutover sites (white bars) for 1999-2002.

7.3 Discussion

7.3.1 Upscaled Chamber Net Ecosystem Exchange

Upscaling chamber estimates of NEE to the ecosystem level at Bois-des-Bel peatland showed a dramatic shift from a system which was a net source of CO₂ to the atmosphere - 239.65 g C m⁻², pre-restoration to a system only two years post-restoration that is a net sink 20.2 g C m⁻² of atmosphere CO₂ during the growing season. Peat respiration significantly decreased post restoration, from ~250 g C m⁻² to ~75 g C m⁻². Not only is the rate of peat respiration decreasing with active rewetting resulting from restoration, but there is also a decrease in the overall peat surface cover as the restored site surface characteristics are more conducive to the establishment of a vegetative surface dominated by both herbaceous vegetation and *Sphagnum* mosses (Figure 4.4). In addition to the increased percent cover of vegetation on the surface of the peatland, this vegetation cover has also been found to have increasing rates of production with increased time post-restoration. Active restoration has definitively increased the sink strength of the cutover peatland as the comparison site still remains a large source of CO₂ to the atmosphere from all its components.

7.3.2 Restoration Implications

Based on the results presented in this study from upscaled chamber estimates of NEE it appears that the process of restoration has converted the Bois-des-Bel peatland from a large net source of CO₂ to the atmosphere to a small growing season net sink of atmospheric carbon dioxide. This is in contrast to previous studies of determining NEE of the restored site of this ecosystem based on micrometeorological techniques which

suggest the site is an even larger source of CO₂ to the atmosphere post-restoration (Petrone et al., 2003). However, simulated NEE exchange estimates based on these initial eddy covariance micrometeorological measurements indicate that the site has the potential to return to a net carbon sink by the end of the sixth year post-restoration (Petrone, 2002). Encouragingly, this study provides promising evidence that ecosystem scale restoration projects of cutover peatlands do have the potential to return to a net carbon sink due in part by active rewetting from the restoration process itself to decrease peat respiration, and in addition the to an emerging vegetation cover within three years post-restoration. Two of the main goals of successful peatland restoration are to have an established *Sphagnum* moss cover as well as to return the net carbon sink function of the system. And in the case of Bois-des-bel, the percent cover of *Sphagnum* moss is on the rise and the results provided in this thesis that at least during the growing season, the site has become a net carbon sink.

CHAPTER 8: CHANGES IN NET ECOSYSTEM EXCHANGE AND BIOMASS FIVE YEARS POST-RESTORATION

8.1 Introduction

Analysis of the changes in peatland CO₂ dynamics post-restoration so far in this thesis have concentrated on the first three years post-restoration. This chapter examines CO₂ fluxes and biomass accumulation five years post-restoration in 2004. The goal of this study season was to measure net ecosystem exchange fluxes from emerging vegetation that was not present at the site in previous study seasons, such as *Carex* species and *Typha latifolia*. Additionally, community scale fluxes were sampled during the 2004 study season, to give an indication of the fluxes from the dominant surface coverages five years post-restoration. The temporal variability in fluxes five years post restoration were also analysed at the diurnal scale, to examine how current vegetation communities respond over the course of the entire day. The net accumulation of biomass at the restored peatland five years post-restoration was also determined.

8.2 Results

8.2.1 Average Biomass Accumulation Five Years Post-Restoration

8.2.1.1 Aboveground Biomass Five Years Post-Restoration

Vegetation species present at the restored site had significantly ($P < 0.05$) greater accumulation of aboveground biomass five years post-restoration as compared to vegetation at the cutover site. The average aboveground estimates at the restored site ranged from $949.74 \pm 533.48 \text{ g m}^{-2}$ for *Carex trisperma* to $333.61 \pm 95.98 \text{ g m}^{-2}$ for *Polytrichum strictum*. In general, herbaceous vegetation had much greater accumulation of biomass as compared to moss species (Figure 8.1). With average herbaceous aboveground biomass at $705.74 \pm 242.48 \text{ g m}^{-2}$ and average moss aboveground biomass at $463.85 \pm 112.81 \text{ g m}^{-2}$ over five years post-restoration.

For the cutover site it is unknown when the vegetation first established at the site, however the site has been abandoned for ~25 years, and thus has the potential to accumulate biomass 20 years longer than the restored site. Cutover site biomass estimates were made from *Polytrichum strictum* and *Ericaceous Shrub* species, with average aboveground biomass of at $338.17 \pm 37.87 \text{ g m}^{-2}$ and $300.3 \pm 62.5 \text{ g m}^{-2}$ respectively, post-abandonment.

Aboveground biomass accumulation for *Polytrichum strictum* is not significantly different ($P < 0.05$) between the restored and cutover sites. Specifically, the cutover site *Polytrichum strictum* average biomass was only 4.6 g m^{-2} greater than the restored site estimate even though it had the potential to be growing for 25 years, as compared to only 5 years in the restored site.

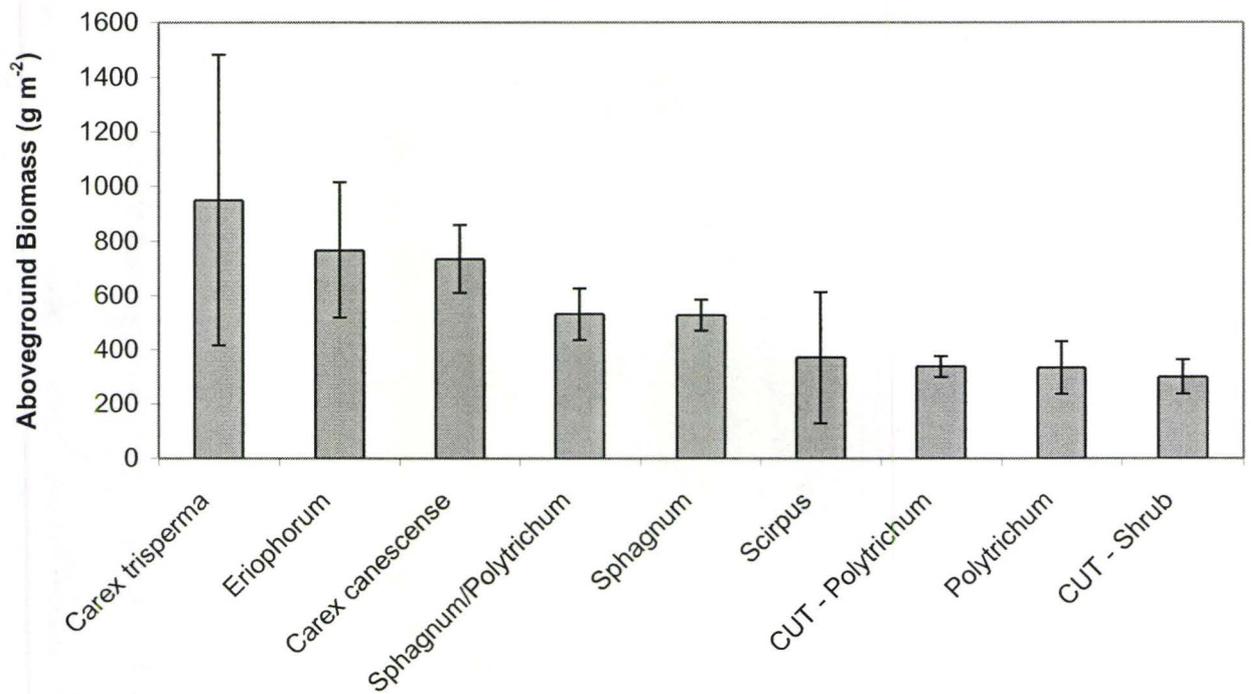


Figure 8.1: Aboveground biomass at the restored and cutover sites, five years post-restoration.

8.2.1.2 Belowground Biomass Five Years Post-Restoration

At the restored site belowground biomass to a depth of 15 cm ranged from $1492.08 \pm 1300.00 \text{ g m}^{-2}$ for *Carex canescense* to $132.63 \pm 127.90 \text{ g m}^{-2}$ for average moss, containing a mixture or both *Sphagnum* spp. and *Polytrichum strictum*. Generally, the amount of belowground biomass declined with increased depth in the peat profile. For example, average belowground biomass from *Carex canescense* ranged from $749.35 \pm 610.06 \text{ g m}^{-2}$ at 0-5 cm depth to 79.58 ± 39.79 at 15-20 cm depth. At the restored site the majority of roots are found in the upper 15 cm of the peat profile (Figure 8.2), with the largest proportion of belowground biomass present in the upper 5 cm of the soil profile. Specifically, restored site belowground biomass in the upper 5 cm of the peat profile ranged from $749.35 \pm 610.06 \text{ g m}^{-2}$ for *Carex canescense* to $111.22 \pm 95.90 \text{ g m}^{-2}$ for *Eriophorum* species. *Scirpus* was the only vegetation type sampled during the 2004 study season with belowground biomass reaching a depth between 20-25 cm, with an average of $46.42 \pm 63.95 \text{ g m}^{-2}$.

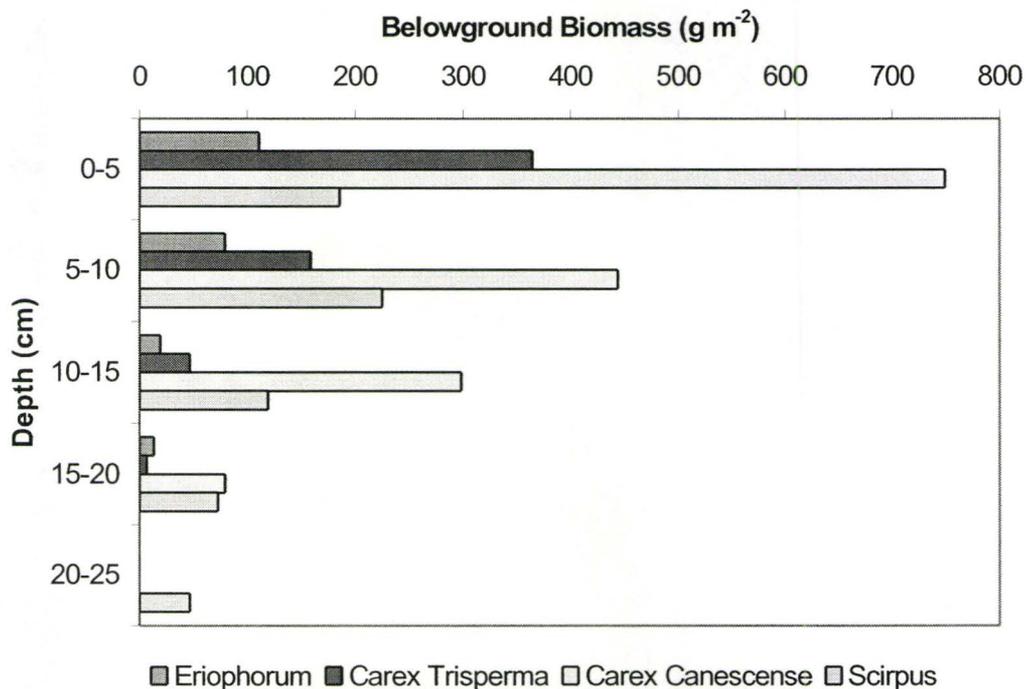


Figure 8.2: Average restored site herbaceous vegetation belowground biomass five years post-restoration.

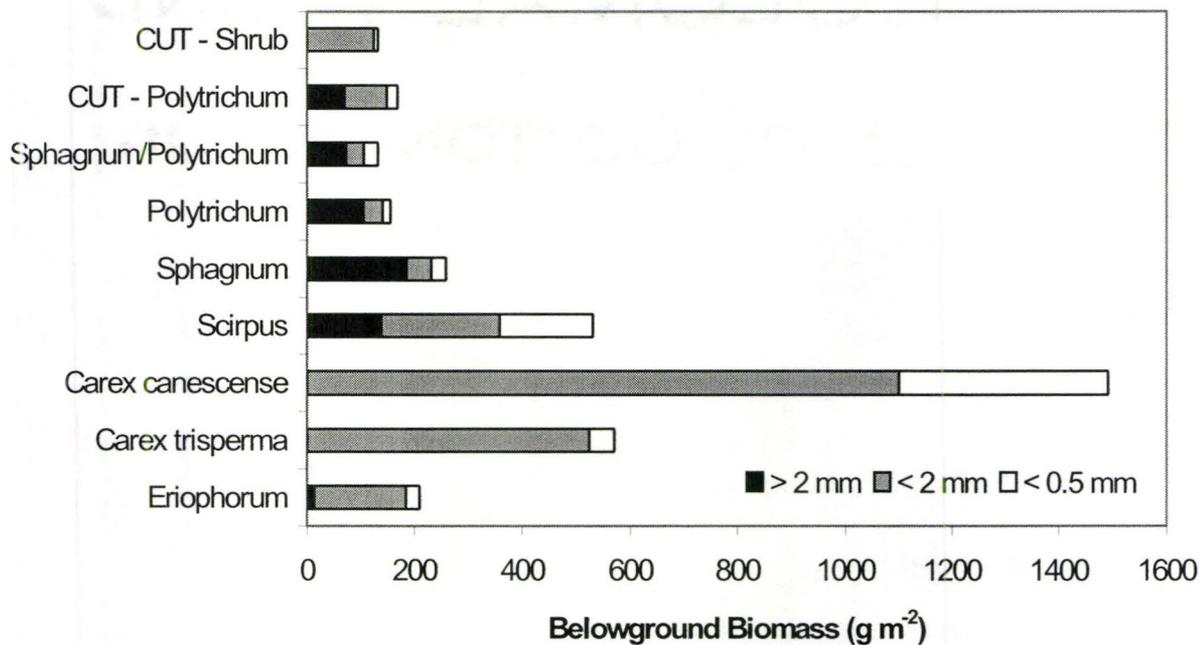


Figure 8.3: Size variation in average belowground biomass five years post-restoration to a depth of 15 cm (g m^{-2}). > 2mm (black bars), < 2mm and > 0.05 mm (grey bars) and < 0.05 mm (white bars).

For the cutover site, average herbaceous vegetation belowground biomass accumulating with time post-abandonment was estimated at $132.51 \pm 9.55 \text{ g m}^{-2}$. This herbaceous belowground biomass estimate is similar to the belowground biomass estimates from moss vegetation at the restored site. No belowground biomass was found below the top 15 cm at the cutover site, with the majority of herbaceous belowground biomass found within the top 5-10 cm of the peat profile.

Belowground biomass estimates also show a variation in size depending on vegetation type and location (Figure 8.3). For restored site herbaceous vegetation, the majority of the belowground biomass estimates made five years post-restoration, were between 0.05 and 2 mm in diameter. For example, *Carex canescense* belowground biomass had $1100.82 \pm 761.55 \text{ g m}^{-2}$ between 0.05 and 2 mm in diameter, and only $391.26 \pm 557.87 \text{ g m}^{-2}$ for less than 0.05 mm in diameter, with biomass in the 0.05 and 2 mm range accounting for ~75% of the total belowground biomass for this vegetation type. In contrast, moss spp., including both *Sphagnum* and *Polytrichum* mosses have a fairly large proportion of coarse roots (> 2mm in diameter) as compared to herbaceous vegetation. For example, the proportion of average belowground biomass from restored site *Sphagnum* mosses with coarse roots (> 2mm in diameter) is ~72%, whereas fine roots only account for 10% of the total. Since moss species are non-vascular, these coarse roots are lateral roots from neighbouring herbaceous vegetation.

8.2.1.3 Total Biomass Five Years Post-Restoration

Total biomass at the restored site five years post-restoration ranged from 2227.23 g m⁻² for *Carex canescense* to 489.32 g m⁻² for *Polytrichum strictum*. These estimates of total biomass ultimately correspond to an annual mean net vegetative uptake of CO₂ (NPP) over five years post-restoration of 222.72 g C m⁻² and 48.99 g C m⁻² respectively (Table 8.1), assuming the annual growth rate is the same in each study season. Total biomass accumulation for the cutover site ranged from 507.28 g m⁻² to 432.82 g m⁻² (Table 8.1), corresponding to an annual mean NPP of 10.15 g C m⁻² and 8.66 g C m⁻² respectively, assuming that vegetation had emerged at the cutover site 25 years prior as it was left abandoned 1980. Therefore, the cutover site has significantly ($P < 0.05$) lower rates of annual uptake (NPP) as compared to the restored site.

Furthermore, the ratio of total above to belowground biomass showed large variability between vegetation types. However, the majority of vegetation species sampled during the 2004 study season were dominated by aboveground biomass (Table 8.1). Above to belowground biomass ratios at the restored site five years post-restoration ranged between 0.50 for *Carex canescense*, to 4.01 for *Sphagnum* spp. and *Polytrichum strictum*. At the cutover site, ratios were not as variable between species, and ranged from 2.00 for *Polytrichum strictum* and 2.27 for *Ericaceous shrub* species.

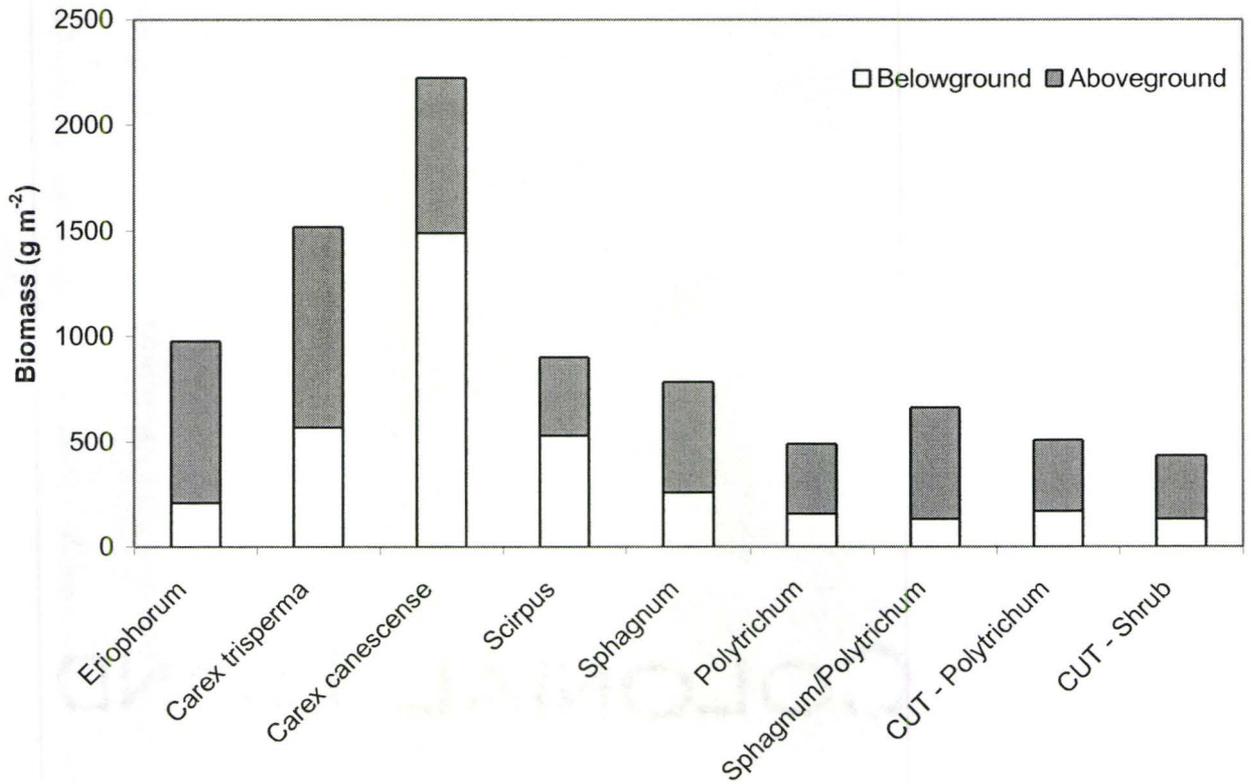


Figure 8.4: Total above (dark bars) and belowground (white bars) biomass for 0-15 cm depth, five years post-restoration at the restored and cutover sites.

Table 8.1: Total biomass (g m^{-2}), average NPP ($\text{g C m}^{-2} \text{y}^{-1}$) and ratio of above to belowground biomass for the a) restored and b) cutover sites, Bois-des-Bel, 2004.

	Vegetation	Total Biomass (g m^{-2})	NPP ($\text{g C m}^{-2} \text{y}^{-1}$)	Ratio of Above to Belowground Biomass
a) Restored Site	<i>Carex canescense</i>	2227.23	222.72	0.49
	<i>Carex trisperma</i>	1520.04	152.00	1.67
	<i>Eriophorum</i>	977.24	97.72	3.65
	<i>Scirpus</i>	901.30	90.13	0.70
	<i>Sphagnum</i>	785.36	78.54	2.04
	<i>Sphagnum/Polytrichum</i>	663.84	66.38	4.01
	<i>Polytrichum</i>	489.32	48.93	2.14
b) Cutover Site	<i>Polytrichum</i>	507.28	10.15*	2.00
	<i>Shrub</i>	432.82	8.66*	2.27

*Cutover site NPP calculated over 25 years (time since abandonment).

8.2.2 Spatial Variability in Net Ecosystem Exchange Five Years Post-Restoration

The seasonal average NEE fluxes five years post-restoration ranged from $24.59 \pm 16.60 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ from *Typha latifolia* to $1.09 \pm 1.11 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ from *Scirpus* (Table 8.2) In general, herbaceous vegetation including *Carex* and *Eriophorum* communities with average fluxes of $12.66 \pm 3.54 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ and $10.61 \pm 3.07 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ respectively have greater seasonal average NEE fluxes as compared to moss vegetation. In addition, fluxes from *Sphagnum* and *Polytrichum strictum* moss species were not significantly different from each other, with the seasonal average NEE fluxes from *Polytrichum strictum*, *Sphagnum* and a mixture of both are $4.58 \pm 2.96 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$, $3.63 \pm 2.15 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ and $2.42 \pm 2.05 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ respectively. Furthermore, the

lowest 2004 seasonal average NEE fluxes measured at the restored site were from *Carex* spp., including *Carex canesensce* and *Carex trisperma*, with seasonal average fluxes of $1.27 \pm 0.73 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ and $1.99 \pm 0.80 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ respectively.

At the cutover site during the 2004 study season, seasonal average *Polytrichum strictum* NEE was a source of CO₂ to the atmosphere ($-3.11 \pm 6.20 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$), whereas the *Ericaceous* shrubs were a small sink of atmospheric CO₂ ($0.86 \pm 0.64 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$). When comparing seasonal average NEE for *Polytrichum strictum* from both the cutover and the restored sites, the *Polytrichum strictum* at the cutover site had a negative average NEE ($-3.11 \pm 6.20 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$), indicating a net release of CO₂ to the atmosphere during the 2004 study season. Whereas the *Polytrichum strictum* located in the restored site ($4.58 \pm 2.96 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$) was on average a net sink of CO₂ over the 2004 study season, leading to an overall difference of $7.69 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ between the two sites.

8.2.3 Temporal Variability in Net Ecosystem Exchange Five Years Post-Restoration

Results from diurnal CO₂ exchange measurements (July 24-25), also indicate that each vegetation type sampled at the restored site five years post-restoration showed a net uptake of CO₂ over a 24-hour period (Figure 8.5). The diurnal average CO₂ fluxes from the restored site range from $2.35 \pm 4.65 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ for *Sphagnum* spp., to $0.84 \pm 6.54 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ for *Polytrichum strictum*. The largest variability in the restored site diurnal fluxes was from *Polytrichum strictum* with the maximum uptake at 09:00 of $13.73 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ to a maximum emission of $-6.23 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ at 00:00.

Table 8.2: Average (\pm standard deviation) net ecosystem exchange (NEE), gross ecosystem production (GEP) and ecosystem respiration (RESP) fluxes under full light conditions for both the a) restored and b) cutover sites, five-years post-restoration.

		NEE	GEP	RESP
a) Restored Site	<i>Ericaceous Community</i>	9.82 \pm 3.41	25.65 \pm 3.98	-12.05 \pm 5.99
	<i>Carex Community</i>	12.66 \pm 3.54	25.72 \pm 1.91	-11.75 \pm 2.33
	<i>Eriophorum Community</i>	10.61 \pm 3.07	22.52 \pm 3.08	-9.11 \pm 4.45
	<i>Typha latifolia</i>	24.59 \pm 16.60	36.39 \pm 16.38	-10.59 \pm 3.21
	<i>Carex canescense</i>	1.27 \pm 0.73	3.29 \pm 1.20	-2.23 \pm 0.73
	<i>Carex trisperma</i>	1.99 \pm 0.80	7.15 \pm 3.09	-5.27 \pm 2.94
	<i>Eriophorum</i>	8.15 \pm 5.63	20.69 \pm 14.14	-12.37 \pm 9.05
	<i>Sphagnum</i>	3.63 \pm 2.15	13.64 \pm 7.31	-10.12 \pm 6.28
	<i>Sphagnum / Polytrichum strictum</i>	2.42 \pm 2.05	14.46 \pm 6.32	-12.35 \pm 4.87
	<i>Polytrichum strictum</i>	4.58 \pm 2.96	17.54 \pm 6.99	-13.61 \pm 4.68
	<i>Scirpus</i>	1.09 \pm 1.11	3.66 \pm 2.91	-3.12 \pm 2.09
b) Cutover Site	<i>Ericaceous Shrubs</i>	0.86 \pm 0.64	9.34 \pm 5.06	-7.42 \pm 4.70
	<i>Polytrichum strictum</i>	-3.11 \pm 6.20	9.03 \pm 4.49	-10.09 \pm 3.93

In contrast, for the cutover site (not shown), the two vegetation species sampled during the diurnal study including both *Ericaceous shrubs* and *Polytrichum strictum* both had negative average NEE fluxes of CO₂ over a 24h period (-0.45 ± 2.10 and -5.77 ± 9.09 g CO₂ m⁻² d⁻¹ respectively), indicating that they were both a source of CO₂ to the atmosphere over this sampling period. Diurnal NEE fluxes at the cutover site ranged from a maximum uptake of 5.30 g CO₂ m⁻² d⁻¹ at 09:00 to a maximum emission of -21.07 g CO₂ m⁻² d⁻¹ at 03:00, both for *Polytrichum strictum*.

In comparing the diurnal NEE CO₂ exchange for *Polytrichum strictum* which displayed the greatest variability in diurnal fluxes at both the restored and cutover sites (Figure 8.6), it is evident that during every sampling interval, the cutover site *Polytrichum strictum* NEE fluxes were lower than the restored site fluxes. Both sites show a general trend of increased CO₂ uptake during the morning and early afternoon and a net release of CO₂ to the atmosphere during the night (21:00 to 03:00). However, due to the large variability in diurnal NEE flux, the average flux for both the restored and cutover site are not statistically significantly ($P > 0.05$) different from each other over the 24-hour period with mean fluxes of 0.84 ± 6.54 g CO₂ m⁻² d⁻¹ and -5.77 ± 9.09 g CO₂ m⁻² d⁻¹ respectively.

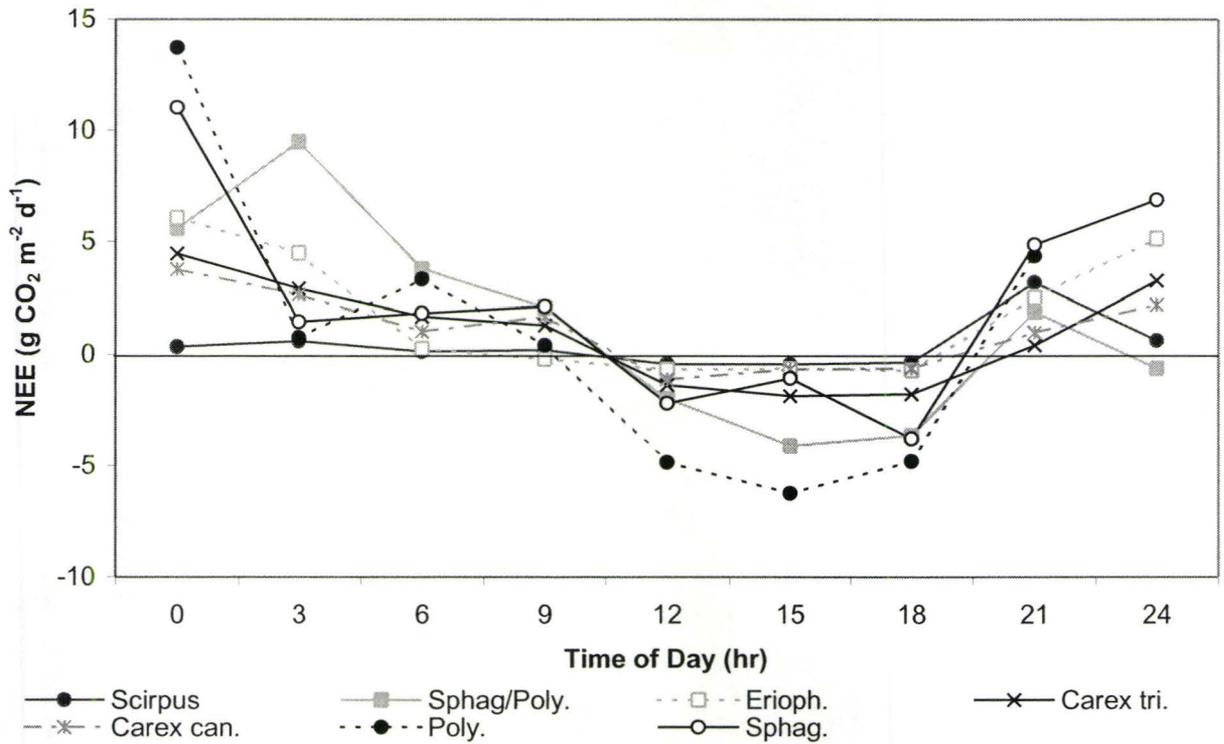


Figure 8.5: Restored site diurnal net ecosystem exchange (NEE) for July 24-25, 2004.

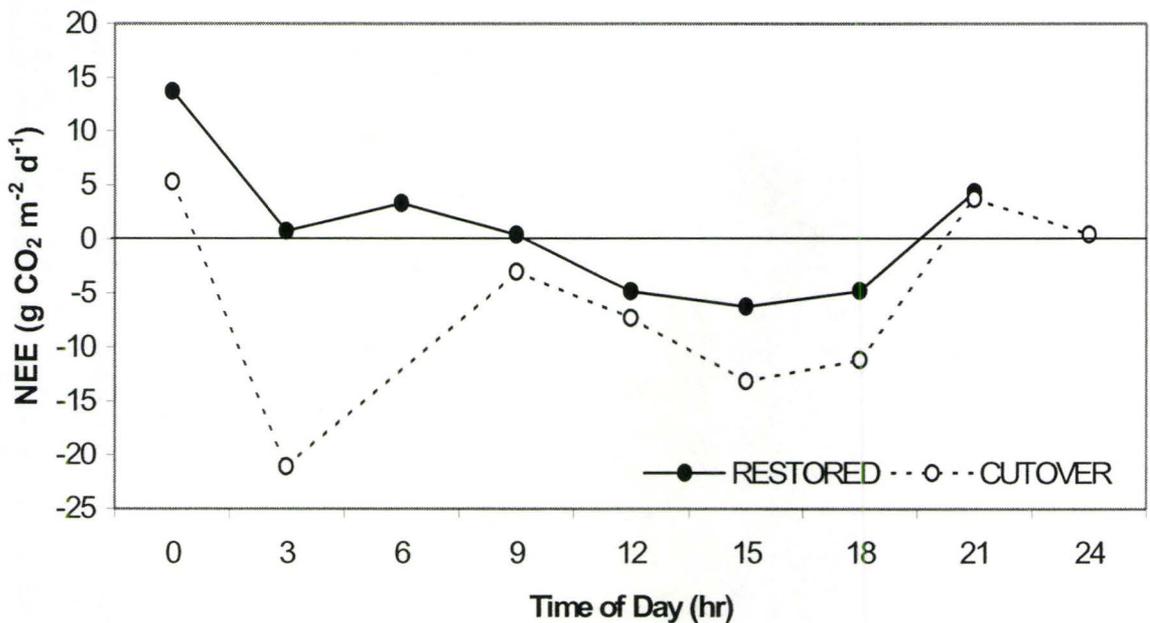


Figure 8.6: *Polytrichum strictum* diurnal net ecosystem exchange (NEE) for both the restored and cutover sites, July 24-25, 2004.

8.3 Discussion

8.3.1 Average Biomass Accumulation Five Years Post-Restoration

The restored site is storing substantial amounts of carbon in above and belowground biomass five years post-restoration. Average aboveground biomass estimates, representing the net vegetative uptake of CO₂ from the restored site over five years post-restoration, range from $949.74 \pm 533.48 \text{ g m}^{-2}$ from *Carex Trisperma* to $333.61 \pm 95.98 \text{ g m}^{-2}$ from *Polytrichum strictum*. Whereas the cutover site, average *Polytrichum strictum* aboveground biomass was estimated at $338.17 \pm 37.87 \text{ g m}^{-2}$ over time post abandonment (25 years). The average aboveground biomass accumulation for herbaceous species are significantly greater than the average biomass accumulation from moss vegetation, with average estimates of $705.74 \pm 242.48 \text{ g m}^{-2}$ and $463.85 \pm 112.81 \text{ g m}^{-2}$ respectively over five years post-restoration. These estimates of herbaceous biomass are greater than studies conducted in natural peatland ecosystems; however, estimates for moss vegetation are similar. For example, Moore et al., (2002), determined that the average aboveground biomass at a bog was 587 g m^{-2} . However the biomass at this study site was mainly composed of shrubs and *Sphagnum* mosses. In addition, a study conducted by Thormann and Bayley (1997a; 1997b), also found that total bog biomass production was $390 \text{ g m}^{-2} \text{ y}^{-1}$, significantly lower than estimates by Moore et al., (2002), and the current study. However, Thormann and Bayley (1997a; 1997b) state that these results maybe significantly underestimated as no belowground biomass data was sampled. Another study conducted by Dyck and Shay (1999), estimated aboveground biomass of plant

communities in two bogs, where the total aboveground biomass ranged from $\sim 720 \text{ g m}^{-2}$ to $\sim 7300 \text{ g m}^{-2}$.

Due to the difficulty of field collection, (Thormann and Bayley, 1997a) and sorting, specifically by separating roots from a saturated, organic matrix (Moore et al., 2002), only a limited number of previous studies have attempted to determine accumulation of belowground biomass in peatland ecosystems. However, it is estimated that up to 90% of the total biomass of wetland plants are found in the belowground tissues (Thormann and Bayley, 1997a), and therefore are important for determining overall vegetative carbon uptake. Belowground biomass estimates made at the restored site in this study to a depth of 15 cm ranged from $1492.08 \pm 1300.00 \text{ g m}^{-2}$ for *Carex canescense* to $132.63 \pm 127.90 \text{ g m}^{-2}$ for average moss collars, containing a mixture of both *Sphagnum* spp. and *Polytrichum strictum*. In addition, the majority of the belowground biomass estimates from herbaceous vegetation made five years post-restoration, were dominated by fine roots with a diameter ranging between 0.05 and 2 mm. A study of belowground biomass in natural bog hummocks and hollows by Moore et al. (2002), show much larger estimates of belowground biomass. For example, the average belowground biomass at bog hummocks was estimated as 2400 g m^{-2} with coarse roots ($> 2\text{mm}$) accounting for $\sim 86\%$ of the total (Moore et al., 2002). However, estimates made at natural bog hollows by Moore et al. (2002) were 1400 g m^{-2} , and were closer to the herbaceous estimates made in the current study. However, in contrast to the current study, coarse roots dominated (70%) the belowground biomass in the study by Moore et al. (2002). Therefore, for the majority of vegetation species sampled at the restored site five years

post-restoration, aboveground biomass dominated the net allocation of carbon, with the total ratio of above to belowground biomass ranging from 0.50 for *Carex canescense*, to 4.01 for *Sphagnum* spp. and *Polytrichum strictum*. Previous studies have found that above to belowground biomass allocation shifts in response to external changes, such as climatic variability. However, in most cases, belowground biomass allocation is dominant in dry, warm conditions (Weltzin et al., 2000) where vegetation shifts carbon allocation, towards root growth in an attempt to gain increased moisture for survival and maintenance, whereas aboveground biomass allocation is greatest in wet conditions (Weltzin et al., 2000). Moreover, total biomass estimates five years post-restoration, indicate that the restored site has adequate moisture conditions necessary for vegetation growth due to the dominance of aboveground biomass allocation at the restored site.

Furthermore, the total biomass accumulation at the restored site ranged from 2227.23 g m⁻² for *Carex canescense* to 489.32 g m⁻² for *Polytrichum strictum*. These total biomass estimates correspond to NPP over 5 years of 222.72 and 48.99 g C m⁻² y⁻¹ respectively, assuming the annual growth rate is the same in each study season. However, the cutover site had significantly reduced rates of NPP. Therefore the total biomass accumulation for the cutover site ranged from 507.28 to 432.82 g m⁻², ultimately corresponding to a NPP of only 10.15 and 8.66 g C m⁻² y⁻¹ respectively. Waddington et al., (2003b) determined that the net production rates of *Sphagnum* spp. from restored peatland plots ranged between 341 ± 17 g m⁻² and 286 ± 13 g m⁻², however estimates of *Sphagnum* net production from Bois-des-Bel, five years post-restoration was significantly lower at 78.54 g C m⁻². As well, NPP estimates made by Moore et al., (2002) from a natural bog were

significantly greater than the estimates made at Bois-des-Bel five years post-restoration, with average aboveground NPP ranging from 158 g m^{-2} to 755 g m^{-2} .

8.3.2 *Spatial and Temporal Variability in Net Ecosystem Exchange Five Years Post-Restoration*

Seasonal mean NEE fluxes for both herbaceous and moss vegetation at Bois-des-Bel exhibit significantly improved net CO_2 fixation, five years post-restoration. Specifically, the average seasonal fluxes of all vegetation types sampled during the 2004 study season at the restored site all displayed positive net ecosystem exchange (NEE). The seasonal average NEE fluxes ranged from $24.59 \pm 16.60 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ from *Typha latifolia* to $1.09 \pm 1.11 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ from *Scirpus*. However, there was a large variability in seasonal mean NEE fluxes from the different vegetation communities present at the restored site five years post-restoration. This deviation in NEE between individual species and communities can be accounted for by the under story vegetation present in community collars. For example, two replicates of the *Eriophorum* community collars have different percent cover of herbaceous and moss vegetation. Specifically, one of the replicates (60E1) contained 25% mosses, 60% herbaceous (*Eriophorum*) and 2% *Ericaceous shrubs*; whereas the second replicate (10E2) contained 65% moss and only 15% herbaceous cover, with the same *ericaceous shrub* cover. The seasonal average NEE of each collar were 11.23 ± 2.94 and $9.98 \pm 4.98 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ respectively. Hence, the collar with the largest proportion of herbaceous vegetation had the largest overall flux.

In addition, results from diurnal CO_2 exchange measurements made five years post-restoration also indicate that each vegetation type sampled at the restored site showed a

net uptake of CO₂ over a 24-hour period. The diurnal average CO₂ fluxes from the restored site range from $2.35 \pm 4.65 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ for *Sphagnum spp.*, to $0.84 \pm 6.54 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$ for *Polytrichum strictum*.

8.3.3 Implications for Restoration

Results of changes in both net ecosystem exchange and biomass provide promising evidence that the Bois-des-Bel ecosystem restoration site has the potential to return to a net sink of atmospheric CO₂ within five years post-restoration. Biomass estimates suggest that the restored site is storing substantial amounts of carbon in both above and belowground biomass, with a dominance of carbon allocation to aboveground biomass for most species present five years-post restoration. Biomass estimates made at the restored site are much lower than natural peatlands, however, the site is still in early successional stages. As well, net ecosystem exchange estimates made under full light conditions also show that each vegetation species sampled five-years post-restoration had a positive seasonal average net ecosystem exchange, meaning that each species represented a net seasonal uptake of atmospheric CO₂. In addition, results from diurnal CO₂ exchange measurements made five years post-restoration also indicate that each vegetation type sampled at the restored site showed a net uptake of CO₂ over a 24-hour period. However, it must be noted that these estimates of net ecosystem exchange were made during a peak in the growing season, between mid July and early August, as such, fluxes maybe overestimated, as winter CO₂ losses from peatlands can attribute to as much as 21% of the net annual release (Alm et al, 2002). However, when restored site net

ecosystem exchange estimates five years post-restoration are compared to the fluxes obtained from the cutover site left abandoned for 25 years, the cutover site still remains a net source of CO₂ to the atmosphere. Therefore, active rewetting from ecosystem scale restoration practices has returned a restored cutover peatland to a seasonal sink of atmospheric CO₂ after only five years.

CHAPTER 9: SUMMARY

9.1 Conclusions

Natural peatlands are important components in the global carbon cycle as they represent a net long-term sink of atmospheric carbon dioxide (CO₂), storing ~23 g C m⁻² y⁻¹ (Gorham, 1991) however, peatland extraction converts these ecosystems to persistent sources of atmospheric CO₂ following abandonment. One of the main goals of peatland restoration is to return the natural carbon sink function of these sites, by both a reduction in peat decomposition as well as an increase in plant productivity at the site. It is essential to determine how restoration affects the rates of peat respiration to assess if the site will return to a net long-term carbon sink, and similarly, to create appropriate restoration techniques and management to achieve this goal. The results presented in this thesis, provide promising evidence that Bois-des-Bel, a full ecosystem scale restored peatland has the potential to return to a net sink of atmospheric CO₂ within three to five years post-restoration.

Peat respiration values at Bois-des-Bel indicates that the seasonal average fluxes are decreasing with time post-restoration which is encouraging for the peat industry that active restoration is successful at reducing peat respiration. However at the same time the peat respiration fluxes from the restored site were not statistically significantly different from those at the cutover site. Therefore, at the current stage in restoration there a trade-off between a reduction in aerobic decomposition and diffusive transport via active rewetting at the restored site and an increase in microbial activity and CO₂ production

potential, making the seasonal average peat efflux not significantly different between sites two years post-restoration.

As well, restoration has produced significant changes in seasonal NEE due to active restoration and rewetting, with seasonal mean NEE fluxes for both herbaceous and moss vegetation displaying significantly improved net CO₂ fixation with time post restoration. Subsequently, rates of GEP have increased over the same period due to emerging vegetation. Light response curves showing the relationship between gross ecosystem production of CO₂ (GEP) and photosynthetically active radiation (PAR) indicate that both the apparent quantum efficiency and the maximum GEP (A_{max}) increased with time post-restoration. Moreover, the percent cover of moss vegetation, namely *Sphagnum* spp., are increasing with time post-restoration. This shift towards *Sphagnum* species will eventually out compete pioneer species such as *Polytrichum strictum* (Groeneveld and Rochefort, 2005) and is a desirable goal of peatland restoration (Rochefort et al., 2003).

Biomass estimates suggest that the restored site is storing substantial amounts of carbon in both above and belowground biomass, with a dominance of carbon allocation to aboveground biomass for most species present five years-post restoration. Total biomass estimates from the restored site correspond to an average NPP over 5 years post-restoration of 222.72 and 48.99 g C m⁻² y⁻¹ respectively.

Previous studies conducted to determine the ecosystem scale net ecosystem exchange of a recently restored peatland have shown a significant increase in the flux of CO₂ to the atmosphere post-restoration (Petroni et al., 2003). The net ecosystem exchange post restoration is approximately double the rates of CO₂ fluxes pre-restoration despite active

restoration techniques. The first and second year post-restoration seasonal NEE averages are $\sim 480 \text{ g C m}^{-2}$ and $\sim 470 \text{ g C m}^{-2}$ respectively. This increase in flux post restoration was suggested to occur due to the lack of a carbon fixing vegetative surface resulting in limited production and highly variable moisture conditions that may have increased CO_2 decomposition in addition to decomposing straw mulch present on the site. However, chamber estimates which have been upscaled to the ecosystem level based on the percent cover of each plant species/land classification, indicate that the restored site, both one and two years post-restoration (2000, 2001) is a net sink of CO_2 over the study season (May-October), storing $\sim 13.5 \text{ g C m}^{-2}$ and 20.2 g C m^{-2} respectively. However, over the same study seasons, it is evident that the comparison site still remains a large source of CO_2 , releasing $\sim 136.8 \text{ g C m}^{-2}$ and 83.0 g C m^{-2} in 2000 and 2001 respectively. These results permit the estimation of the potential magnitude of carbon sequestration in abandoned, cutover peatlands in Canada, if active restoration was employed. Currently, $\sim 12\,000$ ha of peatlands are cutover in Canada (Cleary, 2003), representing less than 0.01% of Canada's total peatland area. Nevertheless, Waddington and Warner (2001) determined that these drained and harvested peatlands represent an annual release of $\sim 0.06 \text{ Tg C}$ to the atmosphere. Furthermore, if these Canadian cutover peatlands were actively restored using upscaled chamber estimates of carbon storage observed two years post-restoration at the Bois-des-Bel peatland (20 g C m^{-2}); restoration could reduce the loss estimated by Waddington and Warner (2001) by $\sim 2.4 \text{ Gg C y}^{-1}$. Consequently, these results indicate active ecosystem scale restoration techniques conducted at Bois-des-Bel have the potential to return the system to a net sink of atmospheric CO_2 . The resultant increased

storage of CO₂ post-restoration can be attributed in part by a reduction in peat respiration via active rewetting, in addition to the significant increase in ecosystem productivity from an evolving vegetative cover.

CHAPTER 10: REFERENCES

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