# THE CARBON DYNAMICS OF A PRAIRIE POTHOLE WETLAND

by

Leah Carolyn Metanczuk Hartwig

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## ABSTRACT

Wetlands are very valuable ecosystems as they play an integral role in wildlife habitat, water management and greenhouse gas exchange. The exchange of carbon dioxide between prairie wetlands and the atmosphere is poorly understood. The purpose of this study was to identify rates and trends in the growing season carbon dioxide flux from the riparian and open-water zone of a prairie pothole wetland. In addition to providing core open water and riparian zone $CO_2$ flux measurements, relationships between variations in $CO_2$ flux and characteristics of the wetland's biological, biochemical and hydrometeorological state were assessed. The $CO_2$ effluxes from the pond during the summer of 2006 were approximately four times greater than in 2005, but were much lower in the early fall. Algal chlorophyll-*a* concentrations were greater in 2005 than 2006 for all three algal assemblages. The mean chlorophyll-*a* concentrations in 2005 for epiphyton, phytoplankton and metaphyton were 2.75 ± 0.62 g $m^{-2}$, 87 ± 24 μ $L^{-1}$, and 318 ± 187 g $m^{-2}$ respectively. In 2006 mean concentrations for the same assemblages were 0.008 ± 0.001 g $m^{-2}$, 8 ± 2 μ $L^{-1}$, and 27 g $m^{-2}$ respectively. The amount of DOC in the open water in August of 2005 (140 mg DOC $L^{-1}$) was 70 times greater than in July of 2005 (2 mg DOC $L^{-1}$). DOC ranged from 30 to 52 mg DOC $L^{-1}$ in 2006. Although highly productive, the pond proper appeared to be a source of DOC which is concurrent with literature from littoral zone and shallow inland waters. Soil respiration increased upslope from the wetland to the cropped upland in 2005. Net ecosystem exchange was greater in the cattail ring surrounding wetland than the grass and sedge zone beyond the cattails. The riparian vegetation may have been water stressed in late-July (at the climax of the dry period) when net ecosystem exchange decreased. Diurnal net ecosystem exchange in the riparian zone indicates uptake during the day and emissions at night. From this data it appears that the riparian zone may have acted as a $CO_2$ sink in June, July and August and a source in April.

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# TABLE OF CONTENTS

## LIST OF TABLES

## LIST OF FIGURES

# 1.0 INTRODUCTION

Wetlands have been receiving more attention in the last decade because of the important role they play in ecosystem-atmosphere gas exchange. This role has become especially important, as the concern of climate change becomes a more prevalent issue. This study has focused mainly on wetlands and $CO_2$ exchange.

Carbon dioxide exchange in wetland ecosystems is of particular interest as it is responsible for about 60% of the anthropogenic greenhouse effect (Rodhe, 1990). In the troposphere $CO_2$ operates as a greenhouse gas by absorbing and re-emitted infrared radiation. In the stratosphere $CO_2$ slows the destruction of $O_3$ by radiative cooling (Shine et al., 1990). The concentration of $CO_2$ in the atmosphere was 379 ppm in 2005, and has been increasing from 1960 – 2005 at an average rate of ~1.4 ppm each year, and currently stands at 383 ppm (IPCC, 2007).

It is important to understand what environmental and biological factors influence the release and uptake of $CO_2$ from wetland ecosystems. While some studies have quantified $CO_2$ fluxes from northern peatlands and bogs, very few studies have examined mineral wetlands in the prairie pothole region of the Northern Great Plains.

The Prairie Pothole Region is a 780,000-$km^2$ area that covers parts of the U.S. (North Dakota, South Dakota, and Minnesota) and the Canadian Prairie Provinces (Manitoba, Saskatchewan and Alberta). Small and abundant, these wetlands originated in the moraines of the hummocky landscape created by the last glaciation (Mitsch and Gosselink, 2000). The Canadian Prairies area 457,736 $km^2$ in area, most of which is used for agricultural purposes. The wetlands in this area occupy 103,391 $km^2$ or 22.6% of the total land cover (Environment Canada, 1993). Unfortunately, conversion to agricultural land has greatly reduced the quantity of wetlands. An estimated 70% of Canada's wetlands have been lost in settled areas (Ducks Unlimited Canada, 2006). Of the wetlands that still remain in this area many are greatly influenced by agricultural practices, mainly through runoff containing pesticides which aide in eutrophication (Forsyth, 1997, Environment Canada, 2001).

These pothole wetlands are an important aspect of the Prairie landscape as they are among the most productive ecosystems in the world (Whittaker and Likens, 1973; Murkin, 1989; Ducks Unlimited Canada, 2006). Wetlands in this region play a major role in waterfowl habitat, providing critical breeding areas for about 21.6 million waterfowl while producing about 50% to

80% of the North American duck population (Van der Valk, 1989). These wetlands also recharge aquifers, provide habitat for amphibians, and support insects and crustaceans which are unique to wetland habitats (Donald et al., 1999). In an agricultural setting wetlands are particularly important for filtering water, buffering the impacts of adjacent land use and moderating the effects of droughts and floods (Ducks Unlimited Canada, 2006). Impacted by agricultural activities these wetlands may not be able to perform their vital roles. An economic value (in terms of natural capital) has been estimated for these wetlands at US \$15,000 $ha^{-1}$ $yr^{-1}$, by Costanza et al. (1997).

Prairie wetlands also play an important role in the global biogeochemical cycle. In general, wetlands can be sinks or sources for greenhouse gases (carbon dioxide, methane and nitrous oxide). Wetlands are sources for a particular gas when the emissions exceed the amount being taken up and stored. The opposite is true for wetlands that are sinks for a particular gas. Very little is known about the state of prairie wetlands in terms of their source or sink capacity. This is because the source/sink state of a wetland is often very dynamic. A wetland may switch from a source to a sink (or visa versa) over a growing season or from one year to the next. It may also be a source for one greenhouse gas and a sink for another.

Because of the complex biogeochemistry of prairie wetlands and lack of literature for these ecosystems, we do not know a lot about how they respond to different environmental forcing factors in terms of greenhouse gas exchange. High latitude wetlands such as bogs, fens and peatlands which are located in Northern Canada are here in referred to as 'northern wetlands'. Although some work has been done on these northern wetlands to better understand the driving factors for greenhouse gas emissions and uptake, (Hamilton et al. 1994; Neumann et al. 1994; Shurpali et al. 1995; Lafleur et al. 1997; Suyker, et al. 1997; Bellisario et al. 1998; Schreader et al. 1998; Griffis et al. 2000; Suyker, 2000; Macrae et al. 2004) this work is not necessarily applicable to prairie wetlands. Prairie wetlands are very different from northern wetlands. Northern fens and bogs can accumulate peat because of the slowed decomposition rate created by anaerobic and cold conditions. Differences such as the production of peat, vegetation, geological setting, and climate make these two ecosystems hard to compare.

The primary objective of this study wass to identify rates and trends in the ice-free seasonal carbon dioxide flux from the riparian zone and open-water zone of a prairie pothole wetland, and to relate observed variation in the exchange to characteristics of the wetland's

biological, biochemical and hydrometeorological state. Sub-objectives are the characterization of carbon exchange dynamics within the open-water zone of the wetland, and it's riparian fringe.

Background information on this topic is provided in Chapter 2. Chapter 3 includes a summary of methods, including a site description, field and lab methodology and an overview of the equipment used. In Chapter 4, I present and discuss the carbon dioxide fluxes from the open water portion of the pond and relate observations to algal dynamics, water chemistry, integrated wetland-upland landscape flux and other environmental parameters. The carbon dioxide fluxes from the riparian zone are the focus of Chapter 5. In this chapter the weekly and diurnal fluxes are assessed in relation to the integrated wetland-upland flux and other environmental parameters. Summary of pertinent results and concluding remarks appear in Chapter 6.

# 2.0 LITERATURE REVIEW

## 2.1 Prairie wetland ecology, hydrology, chemistry and geomorphology

### 2.1.1 Closed basin wetlands

Closed-basin wetlands in the Prairie Pothole Region are also referred to as depressions under the hydrogeomorphic wetland classification system (Brinson, 1993). These depressional wetlands receive water primarily from precipitation, runoff (from surface or shallow subsurface flow) or groundwater. Water quality in these wetlands is often associated with the dominant water source, and their water chemistry is highly variable (Whingham and Jordan, 2003). Depending on their water source some of these 'closed basin' Prairie depressions may be hydrologically linked to adjacent ecosystems. The adjacent uplands of Prairie pothole wetlands greatly influences their hydrology and water quality (Hayashi et al. 1998a). Closed-basin wetlands are considered nutrient sinks, however, no pattern has been determined for nutrient retention or transport from these depressions (Whingham and Jordan, 2003).

### 2.1.2 Hydrology

Due to the aridity of the Prairie pothole climate, potential evapotranspiration often exceeds precipitation, creating conditions that leave wetlands vulnerable to atmospheric water demand (Conly and Van der Kamp, 2001). These wetlands often have a negative water balance (with respect to the atmosphere). Excess evaporation has been found to range from –10 cm in Iowa to –60 cm in southwestern Saskatchewan (Winter, 1989). A high evapotranspiration to precipitation ratio is characteristic of Prairie potholes and may result in highly saline wetlands producing extreme salinity values as high as 370 parts per thousand (Mitsch and Gosselink, 2000).

The hydrology of these wetlands is highly dependent on snowmelt (Hayashi et al., 1998; Winter, 1989), and to a much lesser extent summer rainfall, surface runoff and subsurface flow (Hayashi et al., 1998a; Conly et al., 2001). The snowmelt is critical for these wetlands because

the melt water is able to travel over the frozen ground and may transfer 30-60% of the total precipitation fallen over the winter from the upland to the wetland (Hayashi et al. 1998a).

Dry and wet cycles are common for prairie wetlands because of their sensitivity to environmental factors (van der Valk, 2005). These wet-dry cycles are responsible for vegetation changes in both seasonal and semi-permanent wetlands. Semi-permanent wetlands with extreme water level fluctuations often experience changes in species composition, whereas seasonal wetlands that have less dramatic water level fluctuations and experience changes in relative abundance (van der Valk, 2005). It has been determined through experimental design that water level fluctuation is the primary determinant of emergent species distribution throughout the Prairie pothole wetlands (van der Valk, 2005).

The water balance of these wetlands is also greatly influenced by their adjacent uplands and the land use associated with it (Van der Kamp et al., 1999). The upland-wetland groundwater flow dynamic is an important factor influencing the geochemical functioning of the wetland (Hayashi et al. 1998b). Wetlands in the Prairie Pothole Region generally receive chemicals via hydrologic transportation, including precipitation and overland flow (Mitsch and Gosselink, 2000). Most of these Prairie pothole wetlands are located in an agricultural setting and the adjacent land use greatly affects the overall functioning of the wetland and is further discussed in the next section.

### 2.1.3 Soils

Prairie wetland soils greatly reflect the biogeochemical transformations within wetlands. The hydric mineral soils of prairie pothole wetlands produce anaerobic conditions that establish a zone for the reduction of nitrogen, sulfur, iron, manganese and carbon (Mitsch and Gosselink, 2000). These mineral soils differ from organic soils (are often associated with peatland wetlands) in that they contain less organic carbon; generally have a higher pH; a lower porosity and water holding capacity; and a higher nutrient availability (Mitsch and Gosselink, 2000).

### 2.1.4 Dissolved oxygen

The solubility of dissolved oxygen (DO) in freshwater wetlands decreases with increasing temperature (Kalff, 2001). DO diffusion rates are influenced by the submersed macrophytes which inhabit the wetland basin. Macrophyte beds can also lead to a reduction in turbulence and therefore a reduction in diffusion rates (Kalff, 2001). These macrophytes can also produce oxygen saturation in the water column through production. However, during the senescence of large populations a reduction in DO in the water column is possible (Wetzel, 2001). This process may create near anoxic conditions throughout an entire lake (Wetzel, 2001). In thermally stratified wetlands or lakes the oxygen concentration in the hypolimnion (produced by the more dense cooler water) is greater than that of the epilimnon (Wetzel, 2001). However shallow ponds exposed to adequate wind action maintain a high degree of mixing and therefore consistent DO concentrations throughout the water column (Kalff, 2001).

Algal and macrophyte photosynthesis increases the DO concentration in the water column, while plant, animal and bacterial respiration consume DO (Kalff, 2001). An increase in organic matter (autochthonous or allochthonous) reduces the DO concentration through decomposition (Wetzel, 2001). Dissolved oxygen levels $< 2$ mg $O_2$ $L^{-1}$, or hypoxic conditions, can be found in wetlands receiving large amounts of decomposable organic matter and reduced organic compounds (Kalff, 2001). Anaerobic conditions occur when soils are flooded. This is due to the very low diffusion rate of oxygen into water (Mitsch and Gosselink, 2000).

### 2.1.5 The carbonate system

The dissolved inorganic carbon content of wetlands is imperative for organic productivity, and regulates the gaseous carbon exchange and nutrient availability (Wetzel, 2001). The dominant forms of inorganic carbon found in wetlands consist of carbon dioxide, carbonic acid, bicarbonate and carbonate and collectively they represent the components of the carbonate equilibrium (Wetzel, 2001). Photosynthesis and respiration are two major factors which influence the amount of $CO_2$ in the water. Photosynthesis, which involves the removal of dissolved $CO_2$, will shift the reaction to the left, which results in the consumption $H^+$ ions and

increases the pH (Kalff, 2002 and Phipps, 2006). Although these factors tend to change the pH of the system the equilibrium reaction acts as a pH buffer.

$$CO_2 + H_2O \longleftrightarrow H_2CO_3 \longleftrightarrow H^+ + HCO_3^- \longleftrightarrow 2H^+ + CO_3^{--} \qquad (2.1)$$

Figure 2.1 The inorganic carbon system (modified from Kalff, 2002)

The pH of the wetland is largely dictated by $H^+$ activity, which in turn is greatly influenced by photosynthesis and biotic respiration (Wetzel, 2001). Natural waters, however, have a buffering system, which aids in the restriction of changes in pH through the maintenance of the carbonate equilibrium (Wetzel, 2001). If the equilibrium reactions are in place (ie. adequate carbonate and bicarbonate ions) the pH will be constant and independent of total hydrated and unhydrated $CO_2$ in solution. The amount of carbonate and bicarbonate will increase with pH under such conditions. Chemical enhancement can increase the exchange of $CO_2$ in the boundary layer (Wanninkhof and Knox, 1996). This occurs in systems with low turbulence and a high pH through hydration reactions of $CO_2$ with hydroxide ions and water molecules.

### 2.1.6 Dissolved organic carbon

The dissolved organic carbon (DOC) content of a water body refers to all of the carbon dissolved in the water column and may include plant, microbial and animal products at various stages of decomposition. The total organic carbon content of 'natural open waters' can range from 1 – 30 mg C liter$^{-1}$, however, much higher values are see in more productive ecosystems such as wetlands (Wetzel, 2001).

DOC can be produced by autotrophic synthesis or heterotrophic metabolism. It is important to note that heterotrophic respiration of organic matter can produce large emissions of $CO_2$ to the atmosphere. Terrestrial and higher aquatic plants produce recalcitrant material which create a major source of DOC in wetlands. Processes such as active secretion, decomposition and lysis that produce DOC in wetlands can be performed by submersed macrophytes, attached algae, phytoplankton and cyanobacteria. In open water zones bacterial degradation and chemosysthesis of organic matter have been found to produce DOC (Wetzel, 2001). DOC can also be transported to wetlands via overland flow or groundwater.

There are various sources of the organic matter each of which translates into different rates of utilization. For example, autochthonously produced DOC often has a much higher initial nitrogen content than DOC from external sources. DOC can also vary in its ability to absorb solar radiation. The optical definition of the potential for DOC to absorb UV and visible radiation is termed chromophoric dissolved organic matter (CDOM) (Wetzel, 2006). Photochemical reactions initiated by CDOM UV and visible light absorption can modify the bonding structure of macromolecules. During such a process, DOC can be converted into dissolved inorganic carbon.

**2.2 Effects of agriculture on prairie wetlands**

Wetlands in the Prairie Pothole Region are generally located in landscapes dominated by agriculture. The adjacent land-use can greatly impact the functioning of the wetland ecosystem. Land-use can affect the hydrology of these wetlands by influencing the infiltration capacity of the soil and/or altering the snow pack configuration leading to changes in timing and amount of snowmelt runoff (Conly and van der Kamp, 2001). Chemicals (such as pesticides and fertilizers) applied to adjacent crops may also enter and affect these wetlands. These chemicals can be transported to wetlands from nearby fields by air (volatilization of the chemical allows it to be carried to the wetland via the wind) and rain (Donald et. al. 1999). Wetlands may also collect these chemicals directly via aerial application (Grover et al. 1997). Herbicide application generally occurs between early May and the first week in July (Donald et al., 2001).

**2.3 Wetland productivity**

Algae and macrophytes are major contributors to the primary production of wetland ecosystems. Macrophytes are aquatic plants that include submersed, floating and emergent plants. Emergent plants (eg. *Typha*) grow in saturated soils and are attached to the substratum via rhizomes or corms (McDougal, 2001). Submersed (eg. Myriophyllum) and floating (eg. *Nymphaea*) macrophytes may attach to the sediment via roots, rhizomes or holdfasts (McDougal, 2001) or may remain free floating (*Ceratpophyllum*).

For the purposes of this review four algal assemblages are considered, they include phytoplankton, epipelon, epiphyton and metaphyton. Phytoplankton refers to the algae suspended in the water column (McDougal, 2001). Epipelic algae are benthic algae associated with bottom sediments. This group of algae consists of mainly mobile diatoms with all movement occurring in the sediment (Robinson et al. 2000). A non-mobile crust of such algae may form on sediments; this is referred to as plocon. Epiphytic algae attach to substrata. It is often found on submersed and emergent macrophytes (Robinson et al. 2000). Algae that form macaroscopic floating mats are referred to as metaphyton and are believed to float because of trapped gases (McDougal, 2001). Although referred to in this study as phytoplankton, suspended algae in the wetland water column may also include epipelon, epiphyton and metaphyton (which are not truly planktonic) and collectively termed tychoplankton.

Until recently, the importance of algae as primary producers and fundamental food sources in wetland ecosystems has been over-shadowed by that of emergent macrophytes. Robinson et al. (1997) were able to highlight and document the importance of algal production as a contributor to total wetland primary production. Metaphyton, however, are often the greatest contributors to algal biomass. In one study by Robinson et al. (1997) metaphyton accounted for about 67% of the total algal annual production in Delta Marsh, Manitoba.

There are many factors that control and regulate photosynthesis and respiration rates in wetlands, including photosynthetically active radiation (PAR), temperature, wind-speed and water availability. External sources of DOC, herbicides, and fertilizers can also impact wetland productivity. Much of the information available about the different production rates of algae is related to one or more of these environmental variables. The relationship of algal production to these variables has lead to the use of models as tools to estimate algal productivity. For example McDougal (2001) used hourly PAR and mean daily Chlorophyll-*a* (interpolated from bi-weekly measurements) to obtain a daily productivity for Oak Hammock Marsh.

### 2.3.1 Macrophyte Production

Table 2.1 contains information on macrophyte productivity from various wetland ecosystems. Macrophyte productivity was studied at Delta Marsh, Manitoba where it was found that belowground biomass was over two times greater than that of the above ground biomass in

both spring and fall (van der Valk, 2000). During the same experiment, Murkin et. al. (2000) measured aboveground and submersed macrophytes over four years to assess the effects of water levels on ecosystem development (through different water-level treatments in different cells). In the medium water-level treatments (30 cm) the submersed aquatic macrophyte biomass ranged from 0 to 61 g/m$^2$. The high water-level treatment yielded a range of 7 to 66 g/m$^2$. *Typha* spp. was only one of many emergent macrophytes measured in this experiment. Alone it yielded between 24 -130 g/m$^2$ in the medium water-level treatment and 47 - 175 g/m$^2$ in the high water-level treatment.

Table 2.1 Macrophyte productivity from various wetland ecosystems and littoral zones

| Wetland type or littoral zone of lake | Emergent (g C/m$^2$/yr) | Submersed (g C/m$^2$/yr) | Total (g C/m$^2$/yr) | Source |
|---|---|---|---|---|
| Sawgrass Everglade wetland Florida | 1346* | | | Daoust and Childers, 1998 |
| Prairie Everglade wetland Florida | 184* | | | Daoust and Childers, 1998 |
| Prairie Marsh (Delta Marsh) Manitoba | | | 338 | Van der Valk, 2000 |
| Prairie Marsh (Oak hammock Marsh) Manitoba, 1997 | 276 | 57 | 964 | McDougal, 2001 |
| Prairie Marsh (Oak hammock Marsh) Manitoba, 1998 | 359 | 45 | 431 | McDougal, 2001 |
| Prairie Marsh (Delta Marsh) Manitoba | 108 | 18 | 329 | Robinson et al. 2000 |
| Lacustrian wetland (George wetland) Wyoming | 87 | 77 | | Hart and Lovvorn, 2000 |

* assuming that 45% of the dry weight is carbon
Total macrophyte biomass may not equal submersed plus emergent macrophyte biomass because in some cases the total also included below ground macrophyte biomass, which is not included in this table.

The percentage of emergent, submersed and floating macrophytes contributing to the total production may change over the course of the season. For example McDougal (2001) found that emergent macrophytes (*Typha*) contributed to 90% of the total productivity in the spring and

only 80% in the latter part of the season. Submersed macrophytes were constant contributing to approximately 10% of the total productivity throughout the season; and floating macrophytes not present in the spring, accounted for the remaining 10% in the latter part of the season.

Macrophyte species richness and production is a function of geologic location and water quality (Lougheed et al. 2001). In this case geologic location refers to factors such as sediment composition and growing season, where as water quality pertains mainly to the nutrient concentration, salinity and clarity of the water. Macrophyte development and thus production is also influenced by wind and herbivory (Hart and Lovvorn, 2000). Wind can create conditions unsuitable for macrophyte growth (through mechanical stress) and herbivory can deplete macrophyte communities.

### 2.3.2 Algal Production

The production rates of the different algal assemblages are dependent on one another mainly through competition. Although phytoplankton increase with increasing nutrient status (Wetzel, 2001), it has also been found that a decrease in metaphyton communities can promote an increase in phytoplankton production (McDougal, 2001).

Although macrophytes can make up a large portion of the total productivity of a wetland, in some cases they may account for the same amount or less than algae. This large contribution to wetland productivity from algae is due to the fact that while macrophytes usually turnover once a season, algae turn over in a matter of days (Robinson et al. 2000) (Table 2.1).

Table 2.2 Turnover Rate of the different algal assemblages (days)

| Wetland type | Phytoplankton | Epiphyton | Epipelon | Metaphyton | Source |
|---|---|---|---|---|---|
| Lacustrine wetland *Wyoming, USA* | 1.2 | 9.3 | 417 | | Hart and Lovvorn, 2000 |
| Prairie wetland (DM*) *Manitoba* | 4.3 | 12.4 | 25.7 | 32.6 | Robinson et al. 2000 |

*DM (Delta Marsh)

Table 2.3 The annual productivity of the different algal assemblages (g C/$m^2$/yr)

| | Metaphyton | Phytoplankton | Epiphyton | Epipelon | Plocon | Source |
|---|---|---|---|---|---|---|
| Prairie marsh (OHM*) *Manitoba* | 481 | 325 | 269 | 3 | 451 | McDougal 2001 |
| Prairie marsh (DM*) *Manitoba* | 430 | 40 | 145 | 6 | | Robinson et al. 2000 |

* OHM (Oak Hammock Marsh) and DM (Delta Marsh)

The hydrology of a wetland plays an important role in regulating biological productivity. This is especially true for prairie wetlands, as they are often linked hydrologically to groundwater, other wetlands, and/or other water bodies via overland flow. Hunt et al. (2005) examined the productivity of periphyton in three hydrologically unique wetlands located in Wisconsin, U.S.A. They found that the rate of periphyton respiration was linked to groundwater interaction with the wetland. From June to October in strong discharge wetlands they found respiration rates of 12.1 ± .86 μL $CO_2$ $m^{-2}$ $hr^{-1}$ where as weak discharge wetlands had slightly lower rates of 11.82 ± 1.44 μL $CO_2$ $m^{-2}$ $hr^{-1}$. Recharge wetlands had significantly lower rates of 6.2 ± .73 μL $CO_2$ $m^{-2}$ $hr^{-1}$. They also found that the strong discharge wetland had 35% and 53% greater periphyton abundances than the weaker discharge and recharge wetlands respectively. This may be because discharge wetlands receive waters rich in nutrients from surface water flow which yields higher productivity and thus more organic matter available for decomposition.

Robinson et al. (1997) examined the algal chlorophyll-*a* concentrations of different algal assemblages in a prairie wetland in relation to different water-level manipulations. The production rates for each of the assemblages and the associated water-level treatments are highlighted in the Table 2.3. Their overall findings were that as water level increases, algal chlorophyll-*a* concentrations decreased with the exception of phytoplankton, which increased. Metaphyton thrive in shallow, nutrient rich waters, and as such produce a colonization ground for epiphytic algae. Abundant metaphyton communities produce unfavorable conditions for phytoplankton (ie. darker, cooler waters with higher competition for nutrients between algae and macrophytes). Therefore, as conditions became less favorable for metaphyton through increasing water levels the lack of competition for nutrients and more hospitable conditions allowed

phytoplankton to increase. Although information exists on biomass production for emergent macrophytes from non-peat forming wetlands, less information is available on biomass production and productivity from algae specific to Prairie pothole wetlands.

Table 2.4 Algal biomass in a Prairie wetland (data from Robinson et al., 1997)

| | **Average biomass (mgChl-a/m$^2$) in different treatments (water level)** | | |
|---|---|---|---|
| **Algal assemblage** | **High** | **Medium** | **Low** |
| Phytoplankton | 11.4 | 6.4 | 4.5 |
| Epipelon | 3.2 | 4.2-4.9 | 4.2-4.9 |
| Epiphyton | 50 | 74 | 74 |
| Metaphyton | 426 | 597 | 556 |

**2.4 Carbon dioxide fluxes from the riparian zone**

The riparian zone (or the wetland fringe) acts as an interface between the aquatic and terrestrial landscape components (Groffman et al., 2000). The biogeochemical processes, including atmosphere-surface trace gas exchange within the riparian zone of prairie wetlands are not well known (Merbach et al., 2002). Riparian areas of inland waters play a potentially important roll in greenhouse gas emissions because of the C and N transformations taking place there (Hanson et al., 1994). These transformations may be magnified for wetlands in an agricultural setting, receiving additional chemical and nutrient inputs from the adjacent cropped upland.

Phipps (2006) used small opaque chambers to measure respiration along a transect running through the riparian zone of the Deep Crop wetland on the Manitoba Zero-Tillage Research Association farm (located just north of Brandon Manitoba). It was found that fluxes from this zone ranged from 12.79 – 88.05 mmol $CO_2$ $m^{-2}$ $day^{-1}$, with cumulative fluxes equalling 9312.54 mmol $CO_2$ $m^{-2}$ over 191 days. Diurnal sampling was conducted and mean daytime

(0600h-1800h) and nighttime (1800h – 0600h) fluxes were calculated as 142.1 mmol $CO_2$ $m^{-2}$ $day^{-1}$ and 147.6 mmol $CO_2$ $m^{-2}$ $day^{-1}$, respectively. Carbon dioxide fluxes from the riparian zone were approximately three times greater than from the open water zone.

Glatzel and Stahr (2002) conducted a study examining the greenhouse gas exchange at a pond fringe in South Germany. The wetland was a small depression located in a hummocky terrain. These depressional wetlands are located in a cool and humid climate with a mean annual temperature of 6.4°C and an average annual rainfall of 1400 mm. To conduct the experiment they used large semi-opaque chambers covering $1m^2$ (512 L), designed to let PAR into the chamber. They recorded a net ecosystem exchange (NEE) range of +220 to -260 mg $CO_2$-C $m^{-2}$ $h^{-1}$ (+439.6 to –519.5 mmol $CO_2$ $m^{-2}$ $day^{-1}$) for this area, with an average of +35 ± 41 mg $CO_2$-C $m^{-2}$ $h^{-1}$ (70 ± 82 mmol $CO_2$ $m^{-2}$ $day^{-1}$). However, the soil organic carbon content showed that the area sequestered 39 g $CO_2$-C $m^{-2}$ $yr^{-1}$ (6660 mmol $CO_2$ $m^{-2}$ $yr^{-1}$). The difference in carbon exchange estimation has been attributed to chamber biases. The chamber data obtained was useful in that it showed a strong correlation with the phenological stage (the periodic biological phenomena that are associated with specific climatic conditions) of the dominant macrophyte (*Phragmites)* present along the wetland fringe. The beginning of the season or growth phase (May to June) started with strong carbon assimilation. This was followed by an increase in carbon loss which corresponded with increasing leaf area index (LAI) and respiration (July to September). The season ended with the senescence period (October) during which carbon emissions decreased.

Although little is known about the greenhouse gas exchange from wetland riparian zones, an economic value is attributed to these features (Rickerl et al. 2000). The wetland buffer zones are particularly important in reducing environmental risks to Prairie pothole wetlands located in agricultural settings. Wetland buffer zones are encouraged around Prairie wetlands as they aid in closing the nutrient cycles and improving species abundance.

### 2.5 Carbon dioxide fluxes from the open water

Greenhouse gas emissions from the open water zone of Prairie wetlands have not been well documented. However, some data is available for ponds and littoral zones in a similar

climate to that of the Northern Prairies. This data provides us with an idea of the magnitude of fluxes, and diurnal and seasonal patterns that may be experienced in Prairie wetlands.

Phipps (2006) measured $CO_2$ fluxes from the open water zone of the Deep Crop wetland, located at the Manitoba Zero-Tillage Research Association farm. Carbon dioxide fluxes were measured using small floating chambers. The $CO_2$ fluxes ranged from 3.21 – 38.94 mmol $CO_2$ $m^{-2}$ $day^{-1}$. Cumulative emissions were 2664.58 mmol $CO_2$ $m^{-2}$ over 191 days (substantially less than the emissions from the riparian zone). Mean daytime (0600h-1800h) and nighttime (1800h – 0600h) $CO_2$ fluxes were 64.0 ± 26.3 and 65 ± 33.6 mmol $CO_2$ $m^{-2}$ $day^{-1}$ respectively. In contrast Bonneville et al. 2007 found the diurnal NEE during the growing season of a cattail marsh consisted of $CO_2$ uptake during the day and emissions at night. Although emissions were fairly consistent at night throughout the season, the daytime uptake peaked in August.

Sellers et al. (1995) examined the $CO_2$ exchange in a wetland pond located at the Experimental Lakes Area (ELA) (located in north-western Ontario) and found a diurnal pattern in aqueous $CO_2$ concentration with a peak occurring during the morning (0900h) and declining to near dusk (2000h) when the lowest $CO_2$ concentration were found. The peak in the morning likely occurred because respiration in the water column transpired throughout the night building up $CO_2$ concentrations, which lead to high early morning concentrations. Photosynthetic $CO_2$ uptake during the day likely resulted in the low values at dusk, at which point respiration dominated NEE. The pond was a net source of $CO_2$ throughout the measurement period with daily emissions ranging from 30 – 4000 μmol $m^{-2}$ $h^{-1}$ (.72 – 96 mmol $CO_2$ $m^{-2}$ $day^{-1}$).

Duchemin et al. (1999) used two techniques to measure $CO_2$ fluxes at the air-water interface of small experimentally created reservoirs with low winds at ELA. The two techniques included the Thin Boundary Layer (TBL) equation and floating chambers. Fluxes calculated using the TBL equation ranged from 118 – 621 mg $CO_2$ $m^{-2}$ $d^{-1}$ (2.7 – 14.1 mmol $CO_2$ $m^{-2}$ $day^{-1}$) in August of the first year and from 26.7 – 536 mg $CO_2$ $m^{-2}$ $d^{-1}$ (.61 – 12.2 mmol $CO_2$ $m^{-2}$ $day^{-1}$) in June of the second year. The chamber method yielded fluxes of 1030 – 3600 mg $CO_2$ $m^{-2}$ $d^{-1}$ (23.4 – 81.8 mmol $CO_2$ $m^{-2}$ $day^{-1}$) and 1260 - 6020 mg $CO_2$ $m^{-2}$ $d^{-1}$ (28.7 –136.8 mmol $CO_2$ $m^{-2}$ $day^{-1}$) for the same time periods (respectively). Mean daily $CO_2$ fluxes acquired using the chamber method were 1930 ± 791 mg $CO_2$ $m^{-2}$ $d^{-1}$ (43.9 ± 18 mmol $CO_2$ $m^{-2}$ $day^{-1}$) in 2000, and 3000 ± 1600 mg $CO_2$ $m^{-2}$ $d^{-}$ (68.2 ± 36.4 mmol $CO_2$ $m^{-2}$ $day^{-1}$) in 2001. The mean daily $CO_2$ fluxes calculated using the TBL equation was substantially less than the chamber method with

values of 293 ± 137 mg $CO_2$ $m^{-2}$ $d^{-1}$ (6.7 ± 3.1 mmol $CO_2$ $m^{-2}$ $day^{-1}$) in the first year, and 163 ± 131 mg $CO_2$ $m^{-2}$ $d^{-1}$ (3.7 ± 3.0 mmol $CO_2$ $m^{-2}$ $day^{-1}$) in the second year. The large difference in fluxes between the two techniques may be due to both an underestimation by the TBL technique (largely because of anemometer position and imperfect parameterizations for transfer velocity) and overestimation by the chamber technique (largely because of chamber artifacts and time of deployment).

Many studies have been done in other wetland and littoral ecosystems in which the systems were net sinks of carbon dioxide (Houghton and Woodwell, 1980; Kling et al. 1991; Bubier et al. 1998; Vesala et al. 2006 and Bonneville et al, 2008;), this is especially true for northern wetlands.

### 2.6 Environmental factors affecting $CO_2$ fluxes from wetlands

Net ecosystem exchange, can be described as the difference between the photosynthetic uptake of $CO_2$ by foliage and the loss of $CO_2$ by root respiration and soil organic matter decomposition (Bellisariao et al. 1998). Water table level, photosynthetically active radiation (PAR), nutrient status and air and soil temperature are the most important variables controlling NEE in northern wetlands (Whiting et al., 1992; Neumann et al., 1994; Shurpali et al., 1995; Whiting et al. 1995; Waddington and Roulet, 1996; Alm et al., 1997 and Griffis et al., 2000). The climatic conditions during the early spring, or pre-green period (when the wetland vegetation is developing) also appear to have a profound impact on NEE. Environmental conditions during the spring greatly impact ecosystem functioning throughout the rest of the season, because of the residual effects on plant growth (Griffis et al. 2000). Wind speed and concentration gradients also affect the rate of $CO_2$ exchange between the soil or open water and atmosphere.

Gross ecosystem production is the amount of carbon fixed by a particular ecosystem through photosynthesis. Under normal conditions it is expected that photosynthetic rates will be highest in the summer months when the PAR is at its maximum. Ecosystem respiration is composed of both heterotrophic soil respiration and autotrophic dark respiration. Lower water table levels (Griffis et al. 2000, Carroll and Crill 1997), drier soil conditions (Griffis et al. 2000) and warm soil temperatures (Carroll and Crill, 1997) were found to increase the rate of ecosystem respiration. Carroll and Crill (1997) found that soil temperature appeared to be the

main driving force for ecosystem respiration. Low respiration rates have been attributed to cold and wet conditions, and usually occur in conjunction with low NEE values (Whiting, 1994). Plant and root respiration generally contribute more to total ecosystem respiration than does respiration from soil. In a study by Whiting (1994) the contribution of soil respiration to total ecosystem respiration was generally less than 20%.

### 2.6.1 Biotic controls on carbon cycling in northern wetlands

Wetland plants not only influence $CO_2$ fluxes to and from the wetland through photosynthesis and respiration, but also though the transport of gases to and from the water-logged sediment. Wetland plants that grow in water-logged (anoxic) soils have developed aerynchyma tissue as an adaptation to these flooded conditions (Esau, 1953). This aerynchyma can be described as the production of large air spaces (also termed lacunae), which provides a means for oxygen to reach the roots (Esau, 1953). This open channel facilitates gas transport to and from the sediment. Carbon dioxide (and other greenhouse gases) can be transported to the atmosphere though the aerynchyma of wetland plants (Thomas et al. 1996), and the process by which gas is emitted through wetland plants is termed pressurized ventilation (Armstrong et al. 1996).

The phenological stage of vegetation is important in the inter-annual variability of carbon exchange from northern wetlands (Griffis et al. 2000). The growth stage and phenology of wetland vegetation are especially important during the pre-green (early spring prior to the majority of the growth) and postgreen (fall or senescence) periods (Griffis et al. 2000). The link between climate and phenology is emerging as a key determinant in the observed variability in global atmospheric $CO_2$ concentrations (Griffis et al. 2000).

A change in the carbon balance of a northern wetland may be determined by changes in trophic status owing to different rates of fine root production, mineralization potential, bulk density of peat and changes in the carbon storage in biomass (Bubier, et al. 1998). In general, the vegetation in northern wetlands has a generally short growing season and small leaf-area-index, both of which results in a small $CO_2$ budget. This small $CO_2$ budget makes these wetlands particularly vulnerable to small changes in climate and can easily switch them from a source to a sink (Schreader et al. 1998).

### 2.6.2 Environmental controls on carbon cycling in northern wetlands

#### 2.6.2.1 Photosyntheically Active radiation (PAR)

Radiation is an important control on NEE because photosynthesis occurs only in environments with adequate light (Churkina and Running, 1998). Although clouds negatively affect the net primary productivity of an ecosystem by reducing photosynthesis, it does not eliminate it all together; plants can use the diffuse radiation to photosynthesize (be it at a lesser rate).

A strong NEE - PAR relationship has been found in many studies (Whiting, G. J. 1994; Suyker et al. 1997; Bubier, et al. 1998 and Schreader et al. 1998). PAR was found to be the most important variable for explaining diurnal variations of NEE in northern wetlands studied by Bubier et al. (1998). Soil temperature at a depth of 5 cm was a close second, followed by water table level (Bubier, et al. 1998). Bubier et al. (1998) also found that at PAR levels above 500 $\mu mol\ m^{-2}\ s^{-1}$ in the mid- and late-growing season of most northern wetlands had a net $CO_2$ uptake.

#### 2.6.2.2 Temperature

Air temperature and soil temperature are among the main factors regulating photosynthesis, respiration rates, and the amount of nutrients available for plant uptake (through its influence on litter decomposition rates) (Churkina and Running, 1998). Because plants growing in northern wetland environments experience such low temperatures the net primary productivity of these plants is limited primarily by temperature. Whiting (1994) found that air temperature could be used as a predicative variable for estimating diurnal variations in total system respiration. Whiting (1994) and Shurpali et al. (1995) found that temperatures greater than 30°C may also greatly reduced photosynthesis in the northern wetland environment. A deep and warm aerobic layer was found to promote respiration rates high enough to exceed the photosynthetic uptake by a stressed sedge community (Schreader et al. 1998).

#### 2.6.2.3 Hydrology

NPP is influenced by the amount of water available to plants, not just by the amount of precipitation. The amount of water available for plant growth is dependent upon: the amount and seasonality of precipitation; soil type; vegetation type; and atmospheric evaporative demand (Churkina and Running, 1998). The hydrology of the wetland also plays a major role in the $CO_2$ exchange rates of the wetland (Lafleur et al. 1997, Bellisario et al. 1998). Water stress due to lack of available water and low water table levels can inhibit productivity in wetlands. A study by Carroll and Crill (1997) found that a northern wetland had low productivity in July and high productivity in August, and suggested that this variability in productivity was due to hydrologic conditions. In July water stress inhibited productivity, while an increase in the water table in August may have helped push productivity to its max. This is an excellent example of how the seasonal carbon balance may be altered by a wetland hydrology.

Many studies suggest that lower than normal water table levels in peatlands will enhance decomposition rates to the point that they are greater than plant production, which would convert them from a net sink to a source of $CO_2$ (Shurpali et al., 1995; Waddington and Roulet, 1996; Carroll and Crill, 1997; Bellisario et al. 1998; Alm et al., 1999; Joiner et al. 1999). Although temperature is the most important variable for explaining respiration on a daily basis, the water table position was found to be most important for explaining the seasonal dark ecosystem respiration, which may be because the water table position is merely an indication of the depth of the aerobic zone (Bubier, et al. 1998).

#### 2.6.2.4 Nutrients

During the growing season there is often a large uptake of nutrients from the sediment by both the submerged and emergent vegetation. By the time the vascular plants senesce, a substantial portion of the nutrient rich sediments have been translocated back to the roots or rhizome along with an equally substantial portion lost to the water through leaching or litter fall (Mitsch and Gosselink, 2000). Nutrient additions to wetlands are an important issue for Prairie wetlands, as most wetlands in the Prairie Pothole Region are located in an agricultural landscape and may receive large nutrient inputs from runoff containing fertilizers. Wetland eutrophication

usually results from an influx of nutrient and produces exceptionally high rates of productivity. Eutrophication of wetlands can produce large areas of anaerobic reducing conditions, and lower rates of organic matter decomposition, in which case the sedimentation occurs. This however is not as important for northern wetlands and has not been studied in depth in northern wetlands.

### 2.6.3 Implications for prairie wetlands

Hamilton et al. (1994) studied several northern ponds one of which had mineral soils (as opposed to organic soil which is common for northern wetlands). Their findings show that the mineral pond had the lowest carbon influxes. This is consistent with a study by Macrae et al. (2004), who found that northern wetlands with soils high in minerals tended to continuously evade more carbon to the atmosphere than wetlands with organic soils. The magnitude of the $CO_2$ efflux tended to increase under wet conditions. These findings may be similar to what we can expect for prairie wetlands, because most wetlands in the prairie wetlands have mineral soils. Organic soils are not often found in the Prairies because the climatic conditions do not favour the accumulation of peat.

There are many differences between the two wetland soils, which have a profound impact on the functioning of the wetland. Mineral soil generally has a lower organic content, porosity and water holding capacity, where as organic soil has a lower nutrient availability and lower (more acidic) pH (Mitsch and Gosselink, 2000).

Prairie wetlands differ from northern wetlands in that they experience a longer growing seasons and more mild winters. This longer growing season may allow for more carbon acquisition, but because the temperature is non-limiting there may also be more decomposition and respiration. The water balance of prairie wetlands is also much different than northern wetlands in that prairie wetlands are usually ‘closed basin’ wetlands that receive water only from runoff, shallow groundwater flow and precipitation. Northern wetlands may be hydrologically linked to other wetlands and/or water bodies, or they may receive water only from precipitation. The hydrological differences between Prairie wetlands and northern wetlands will have a large impact on the carbon budget of the wetland, because hydrology is one of the main factors controlling $CO_2$ exchange at the wetland-atmosphere interface.

Because Prairie pothole wetlands are often located in an agricultural landscape, they receive a large portion of runoff and shallow groundwater flow contaminated by fertilizers, herbicides, and organic matter from the cropped upland. This has immense implications for the carbon budget of these wetlands.

The hydrological and biogeochemical differences that exist between Prairie and northern wetlands must be taken into consideration when comparing the biotic and environmental controls on carbon cycling between the two wetland ecosystems. With this in mind, the array of information available for northern wetlands may give some insight into the potential environmental controls $CO_2$ exchange and periods of importance, which may aid in the understanding of the carbon balance of prairie pothole wetlands.

# 3.0 METHODS

All research was conducted at the Deep Crop wetland of the Manitoba Zero-Tillage Research Association farm during 2005 and 2006. Carbon dioxide fluxes from the riparian zone were recorded during the ice-free season of 2005 and 2006. Four times throughout the 2006 growing season a 24 sampling took place. Continuous $CO_2$ fluxes at the water-atmosphere interface were recorded at a scaffold located in the center of the wetland. These measurements were recorded for approximately one week and took place four times throughout the 2006 growing season and three times in 2005. Algal chlorophyll-*a* and biomass samples were collected on a weekly basis (when available). A basic vegetation survey and biomass harvesting of the riparian zone took place. Continuous measurements of basic water chemistry, basic meteorology and eddy correlation derived $CO_2$ fluxes were recorded at a scaffold located in the center of the wetland.

## 3.1 Field site and sampling design

Research was conducted at the Deep Crop Wetland located on the Manitoba Zero-Tillage Research Association farm (MZTRA). The farm is located roughly 20 minutes north of Brandon Manitoba, Canada in the Prairie Pothole Region (Figure 3.1). The landscape in this area consists of hummocks and hollows creating the ideal landscape for isolated wetlands. The Deep Crop Wetland has been classified as a semi-permanent or Class IV wetland (Stewart and Kantrude, 1971), and consists of a dense ring of cattail (*Typha* spp) surrounding a large open water zone (Phipps, 2006). Soils in this area are often Orthic Black Chernozems or Rego or Calcareous Black Chernozems (Phipps, 2006). The cropped upland is gently sloping (2-5%) and the adjacent crop was seeded with Alfalfa during 2005 and 2006. Climactic conditions for the 2005 and 2006 growing season (May to September) as recorded at the Brandon Airport (between 1971 and 2000) are highlighted in the Table 3.1 (Environment Canada, 2006). Figure 3.2 shows the location of the transects at the Deep Crop Wetland.

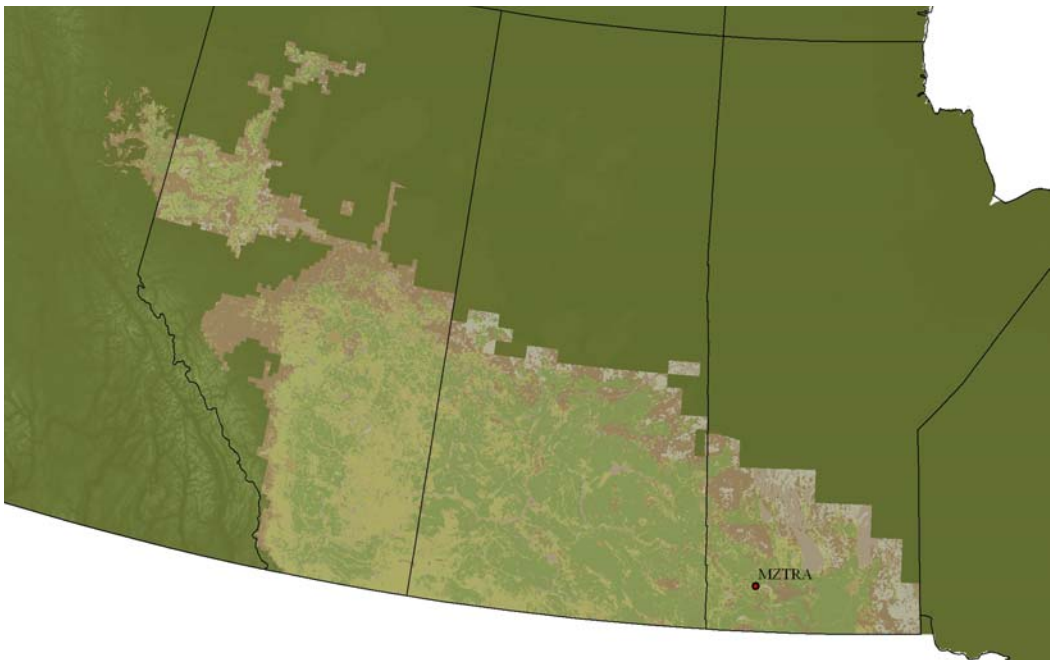


Figure 3.1 Prairie Pothole Region

Table 3.1 Comparison of growing season climate normals with the 2005 and 2006 climatic conditions as recorded at the Brandon Airport (Environment Canada, 2006)

| Month | 1971-2000 (Climate Normal) | | 2005 | | 2006 | |
|---|---|---|---|---|---|---|
| | **Average Monthly Temperature (˚C)** | **Total Monthly Precipitation (mm)** | **Average Monthly Temperature (˚C)** | **Total Monthly Precipitation (mm)** | **Average Monthly Temperature (˚C)** | **Total Monthly Precipitation (mm)** |
| *May* | 11.4 | 52.7 | 9.3 | 56.8 | 11.6 | 41 |
| *June* | 16.1 | 74.4 | 16.3 | 216.2 | 17.2 | 81.6 |
| *July* | 18.4 | 75.8 | 18.9 | 130.2 | 19.9 | 7.8 |
| *August* | 17.5 | 69.2 | 16.6 | 18.4 | 18.8 | 76.4 |
| *September* | 11.4 | 50.1 | 12.5 | 10.4 | 12.1 | 74.6 |

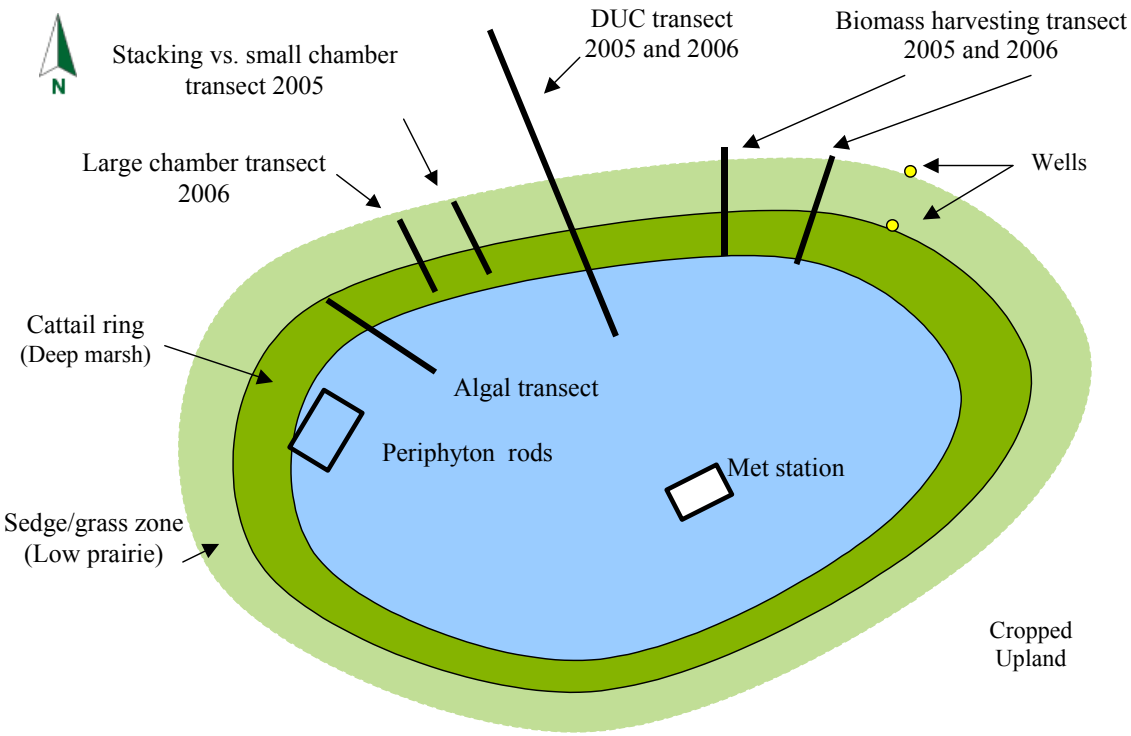


Figure 3.2 Deep Crop wetland schematic

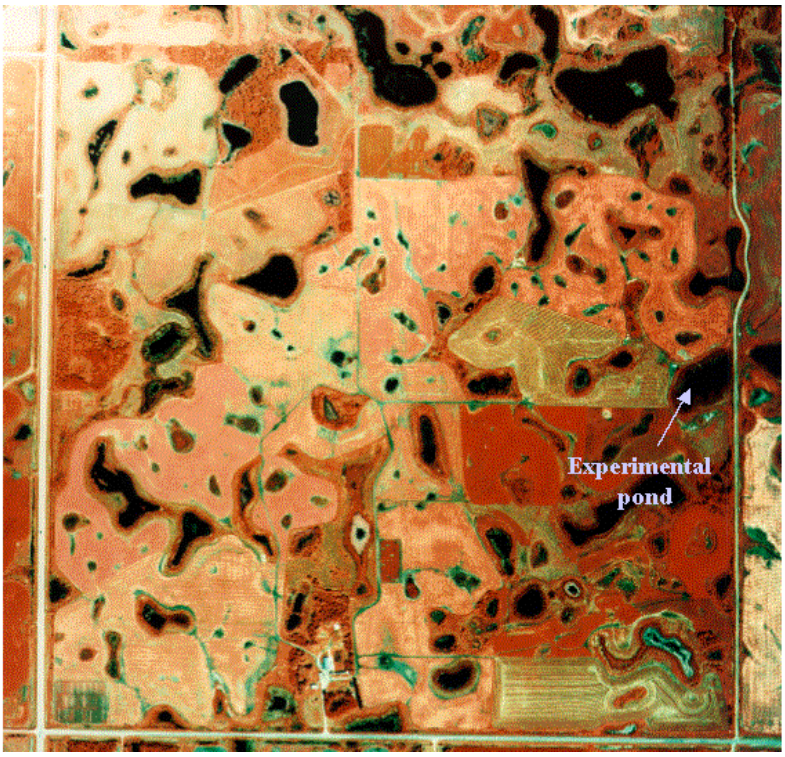


Figure 3.3 Infrared Map of MZTRA Farm

### 3.2 Air temperature, soil temperature, water temperature and soil moisture

Air temperature was measured with a Traceable Long-Stem Thermometer (Fisher Scientific Company, Ottawa, ON) at 5cm above the ground at each chamber location during the gas sampling procedure. At this time soil or water temperature (whichever was present) was measured with the same instrument at each chamber location at a depth of 5cm below ground. During sampling triplicate samples of percent soil moisture were analyzed at each chamber location, using a ThetaProbe Soil Moisture Sensor - ML2X (Delta-T Devices, Cambridge, England), and an average was derived.

### 3.3 Water Quality and chemistry

Basic water chemistry including salinity, temperature, pH, turbidity, redox, and electrical conductivity was measured continuously at the scaffold with a Hydrolab DS 5X (HACH Environmental, Colorado, US). There were a few weeks during the summer when basic water chemistry data is not available because of power problems. Unusual dissolved oxygen values were obtained from the Hydrolab during both growing seasons, which may have been due to sensor malfunction. The dissolved oxygen data has been included in the results chapter, it must be noted however that the absolute values may be off due to sensor failure.

Three times throughout both of the growing season samples were taken and analyzed for nutrients (Ammonia-N, Nitrate and Nitrite as N, total Phosphorus, and total Kjeldahl nitrogen). Dissolved inorganic carbon and dissolved organic carbon were measured in May, June and August of 2006. In 2005 dissolved organic carbon was measure in May, June, July and August.

### 3.4 Chamber sampling

#### 3.4.1 Large chambers

Fluxes of $CO_2$ were sampled using large canopy-scale chambers on a weekly basis at the Deep Crop Wetland from April 27 to September 14, 2006. A few weeks were missed at the beginning of the season between April 27 and May 25. Sampling took place between 1000 and

1400 hours, during periods with no rain. The transect was located in the riparian zone and consisted of five points which started up land in the sedge and grass dominated community and ended in the water logged soils of the cattail (*typha* spp.*)* ring surrounding the wetland (Figure 3.2).

Five metal collars were permanently installed along this transect. Three of the five collars were installed in the upland portion of the transect at the beginning of the season. The other two, were installed closer to the water later on in the season. The sedge/grass area will herein be referred to as the 'Low Prairie zone', and the cattail area will be referred to as the 'Deep Marsh zone' (according to Stewart and Kantrud, 1971). The collar names and positions are highlighted in the Figure 3.4 and Figure 3.5.

Each collar covered an area of 0.495 $m^2$ and was designed with a trough around the perimeter that was filled with water during sampling. This was done to ensure an air tight seal was created when the chambers were placed on top. Clear and opaque chambers were used at each collar. The clear chamber measured net ecosystem exchange and the opaque chamber measured respiration. Two sizes of chambers were also used. Large-short chambers were used in the grass and sedge area and the large-stacking chambers were used in the cattails. The large-short chamber had a total volume of 0.098 $m^3$ and the large-stacking chamber, which was simply an extension plus the large-short chamber, had a total volume of 0.310 $m^3$.

An Infrared Gas Analyzer (IRGA) (Li820 $CO_2$ gas analyzer LICOR Inc. Lincon, Nebraska, USA) was used to measure the $CO_2$ concentration with in the chamber. The chambers were designed with two quick disconnect ports (for the IRGA input and output), a vent, and a small battery powered fan to keep air circulating during the sampling. Chambers were first connected to the IRGA (which created a closed path system) then gently placed on the collar. The IRGA began sampling 30 seconds after the placement of the chamber on the collar and continued sampling for 10 to 20 minutes. The IRGA recoded $CO_2$ concentrations in the chamber every 10 seconds. Once sampling was completed the IRGA was disconnected and the chamber was aired out, to ensure no elevated or lowered $CO_2$ concentrations remained in the chamber for the next sampling point.

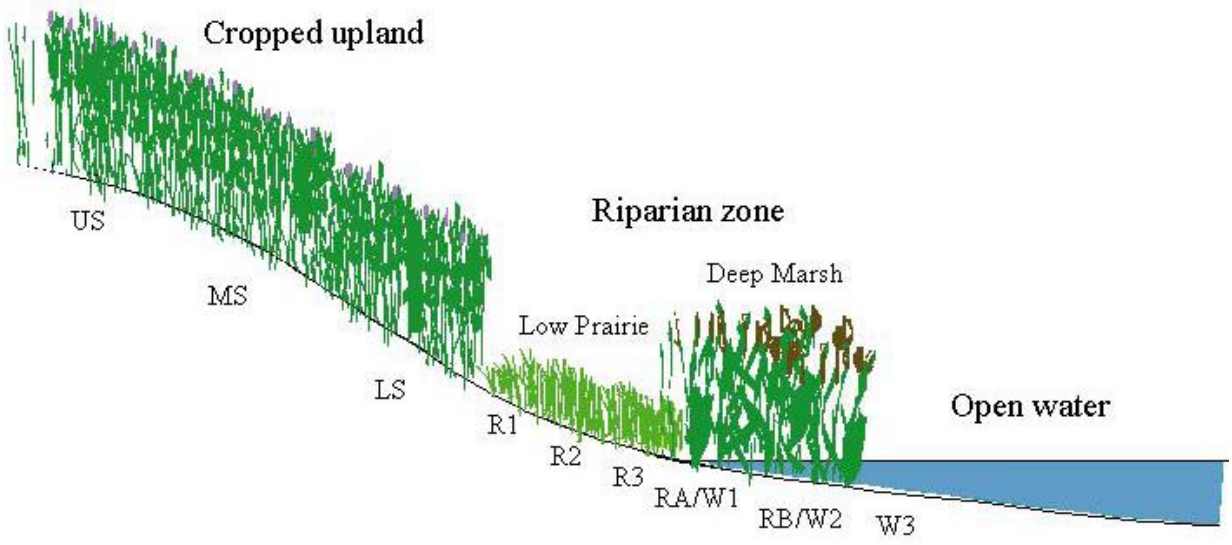


Figure 3.4 Wetland transect schematic

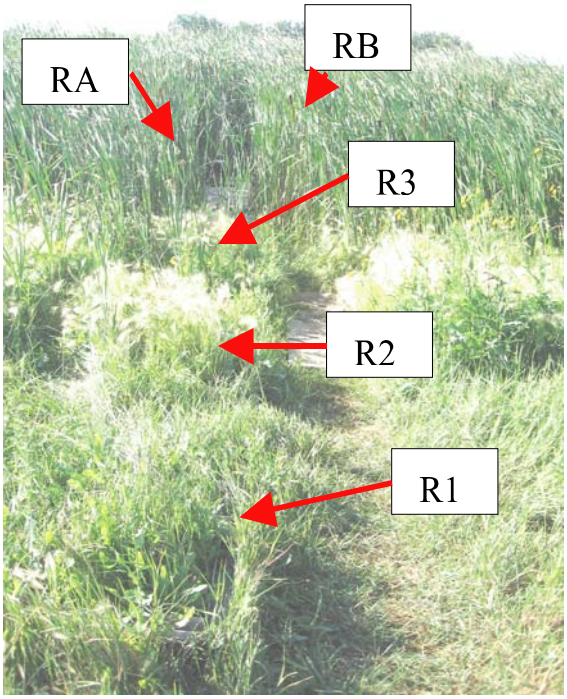


Figure 3.5 Location of points along transect used for large chamber gas sampling

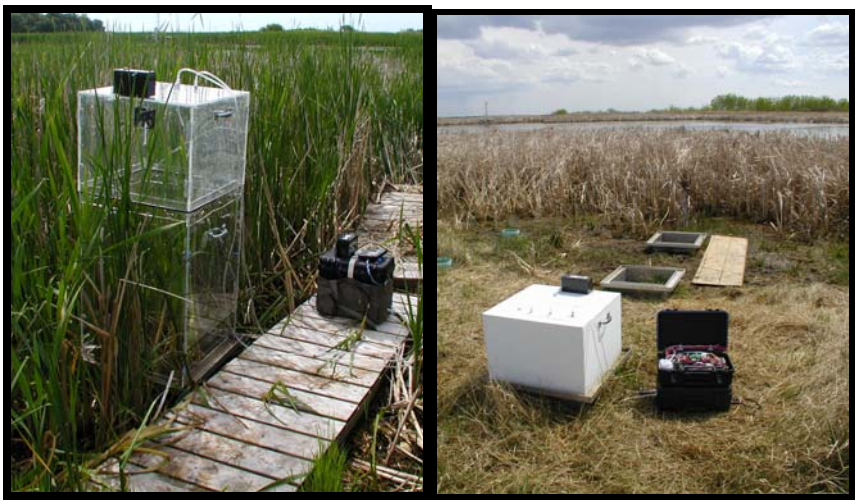

Figure 3.6 Photograph of the clear stacking (right) and opaque (small) chambers

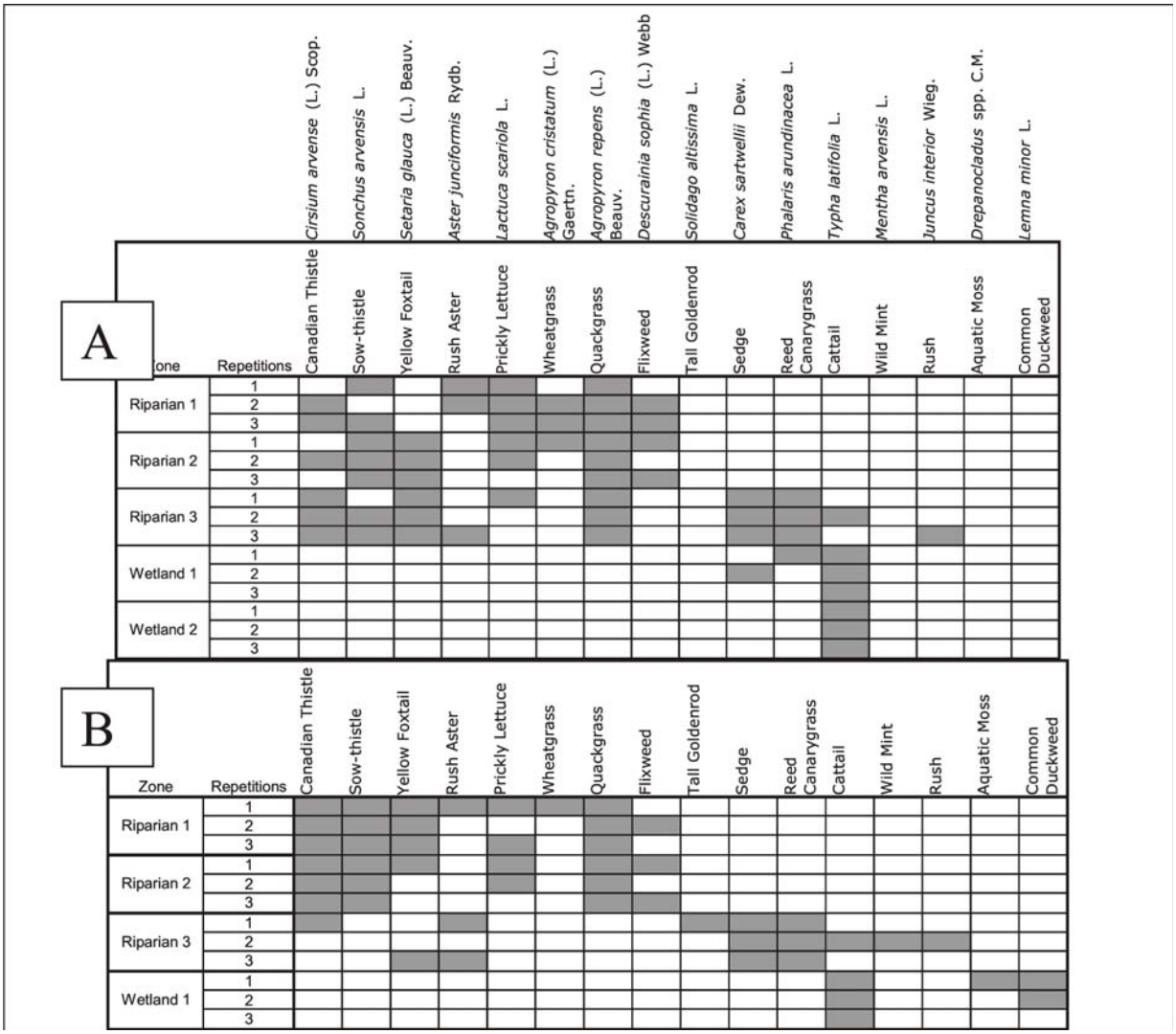


Figure 3.7 Vegetation Survey 2005 (B) and 2006 (A)

Diurnal sampling was conducted four times over the 2006 growing season (once in April, June, July, and August) using the same chamber sampling procedure as indicated above. The clear chambers were omitted during periods with no sunlight. The diurnal sampling began at 1100 hours and ended at 0700 hours the following day, with sampling taking place every four hours.

Flux calculations were made based of the equation from Steduto et al. (2002). This $CO_2$ flux equation was derived for a closed-system chamber sampling method. The study from which the equation was derived was similar to this study in that the chamber volumes were similar, the sampling intervals were similar, and the basic equipment was similar (metal collars and Plexiglas chambers with circulating fans). The equation states that the flux is equal to the change in the concentration of $CO_2$ over time in relation to volume, surface area, and the ideal gas law constituents (Equation 3.1). Because this particular data set was fairly linear, a concentration regression was used. The flux was obtained by finding the slope of the linear regression of the change in $CO_2$ concentration over time.

$$A=(\Delta c/\Delta t)(V/S)(Pa/RT) \qquad (3.1)$$

Equation 3.1 Chamber flux calculation equation (Steduto et al., 2002)

Where c is the mole fraction of $CO_2$ (umol/mol), t is the time (s), V is the volume of the chamber ($m^3$), S is the surface area of the collar ($m^2$), Pa is the atmospheric pressure of the gas inside the chamber (kPa), and T is the temperature in the chamber (K)

### 3.4.2 Small chambers

Small chambers were used along a transect that ran from the cropped upland through the riparian zone and into the open water. This transect was sampled eleven times throughout both 2005 and 2006 by University of Manitoba staff. There were nine landscape positions along the transect with two collars installed at each position (Figure 3.2). There were three positions in the cropped upland: one in the upper slope; one in the mid slope; and one in the lower slope. The three points in the riparian zone corresponded to the three points in the low prairie zone of the large chamber transect. Of the three points in the open water and cattails, the point closest to the periphery corresponded to the point located in the deep marsh zone of the large chamber transect. Of the remaining two points, one was positioned further from shore and the other was located near the center of the pond in the open water.

Soil chambers consisted of a collar, which was installed in the ground at the 12 points running through the upland and riparian zones, and a lid that was positioned on the collars at the time of sampling. Floating chambers were used in the cattail and open water zone. These were situated on top of the water for sampling and removed after (a more detailed description of the chamber design is available in Phipps, 2006). Gas samples were collected by drawing gas from the chamber with a syringe at 30 and 60 minutes after the deployment of the chambers. Samples were collected between 0900 and 1400 hours. Gas analysis was preformed on a Varian CP 3800 gas chromatograph (Varian Canada Inc. Mississauga, ON). Detailed information on the chamber sampling method, gas analysis and flux calculations can be found in Phipps (2006).

### 3.4.3 Stacking chambers

In order to better understand the influence of vegetation on respiration fluxes, stacking chambers were paired with small soil respiration chamber along a transect located in the Low Prairie zone. The data collected are presented in Phipps (2006). Carbon dioxide fluxes from both chamber types were sampled bi-weekly from June 9, 2005 to October 11, 2005. The transect consisted of three small and three stacking chambers (corresponding to R1, R2, and R3). The small chambers were the same as the small respiration chambers (described in Section 3.4.2) and had a headspace volume of 1.62 L covering a surface area of 0.03 $m^2$. The vegetation in these small chambers was trimmed periodically. The stacking chambers consisted of three sections of PVC pipe and had a potential headspace of 14.02 L and covered the same surface area as the small respiration chambers. Gas samples were taken at intervals of 0, 8, 16, 24, 40, and 60 minutes, and analyzed according to Phipps (2006).

## 3.5 Algal sampling

The three algal assemblages that were sampled for chlorophyll-*a* over the 2005 and 2006 growing seasons include, epiphyton, phytoplankton and metaphyton. Phytoplankton and epiphyton samples were collected on a weekly basis and analyzed for chlorophyll-*a*. Metaphyton biomass was also collected and measured on a weekly basis (when metaphyton was present). In 2006 algal sampling commenced May 8$^{th}$ and ended September 25$^{th}$. In 2005 algal sampling

took place between April 30th and September 11th. Phytoplankton and epiphyton sampling procedures were the same for 2005 and 2006. Metaphyton biomass was sampled in 2006 where as metaphyton chlorophyll-*a* was sampled in 2005 and thus different sampling procedures were required. Algal chlorophyll-*a* analysis was conducted by Phipps (2006). Analysis of chlorophyll-*a* for metaphyton, phytoplankton and epiphyton were the same for both years with the exception that a fluorometer was used for chlorophyll-*a* in 2005 and pheophyton pigment analysis whereas a spectrophotometer was used in 2006. Details on algal analysis in 2005 and the associated fluorometer which was used are available in Phipps (2006).

### 3.5.1 Phytoplankton

Phytoplankton was sampled weekly at the end of a dock that extended into the open water zone of the Deep Crop Wetland. A depth integrated water column sampler consisting of a stoppered acrylic tube with a 6.4 cm inner diameter and a length of 50 cm was used to collect the samples. A 500 ml portion of this sample was filtered through a 1.2 micro-meter pore size glass microfiber filter (grade GF/C, Whatman International Ltd., England). The filters were then neutralized with a saturated $MgCO_3$ solution and frozen for a minimum of 24 hours (to allow the cell membranes to lyse) before chlorophyll-*a* analysis.

The analysis process began with thawing the filters and filling the vials with 10 ml of a 90% ethanol solution. The vials were then placed in the dark for 24 hours to allow the extraction of chlorophyll pigments. In 2006 the pigment extract was analyzed using an Ultrospec III spectraphotometer (Biochrom Ltd.,Cambridge,England). Measurements of chlorophyll-*a* were then made at 665 and 750 nm. The samples were then acidified with a $10^{-3}$ N HCl solution and placed in the dark for 1 hour and re-measured at 665 and 750 nm. Calculations of chlorophyll-*a* ($\mu g\ L^{-1}$) followed the procedures from Marker et al. (1980).

### 3.5.2 Epiphytic periphyton

Epiphytic periphyton rods were installed on April 26th in 2006, and April 30th in 2005. A one-week colonization period was allotted prior to the start of the sampling period. Acrylic rods with a diameter of .64 cm were cut into 90 cm lengths (and pre-scored at 2.5 cm increments. The

rods were installed to create a 15 x 4 grid containing 60 rods. Each rod was inserted into the sediment such that approximately 15 cm of water was above the top of the rod. The rods were spaced 25 – 30 cm from each other and were located at the cattail-open water interface. Each week three rods were randomly selected and extracted. Three of the 2.5 cm segments from each rod (one from the upper segment, one from the middle segment and one from the lower segment) were collected and stored in labeled vials and frozen until the time of analysis. The samples were analyzed as per phytoplankton except that the rod segment (not filter) was used for analysis.

3.5.3 Metaphyton

Sampling methods for metaphyton differed between years. When metaphyton was present it was collected for chlorophyll-*a* analysis (in 2005) and biomass (in 2006). Both sampling techniques included the use of a styrofoam block which was placed under the metaphytic mat and allowed to rise to the surface. For chlorophyll-*a* analysis a copper cylinder was used to core a 1.54 $cm^2$ area of the metaphytic mat. Triplicate samples were taken and placed in a labeled 14.8 ml vial and frozen until analysis. The metaphyton chlorophyll-*a* analysis procedure is the same as for phytoplankton except that in this case the entire metaphyton core (not filter) is placed in the methanol solution. In 2006 metaphyton biomass samples were taken using a 144 $cm^2$ quadrat. These samples were dried to a constant weight at 104ºC for 24 hours for the determination of dry weight. Metaphyton dry biomass weight is converted to chlorophyll-*a* using a Chl:biomass ratio of .0025 (Goldsborough, 2001).

**3.6 Biomass harvesting and vegetation survey**

Submerged macrophyte biomass harvesting took place two times over both growing seasons, once in June and once in July. An open ended cylinder (covering an area of 0.23 $m^2$) was placed on the surface of the sediment and long handled sheers were used to collect the entire above-sediment portion of the submersed macrophytes. The sample was then dried at 104°C to a constant weight.

Emergent macrophyte biomass samples were collected in mid August (when emergent macrophyte growth was at its peak). Random triplicate samples were taken from points along a

transect which corresponded to the points along the chamber sampling transect. The above ground portion of the plants with in the quadrat were harvested and dried at a 104°C to a constant weight.

A vegetation survey was conducted in both years and was done using a transect with similar vegetation to the chamber sampling transect. A quadrat was then placed randomly at points along the transect that corresponded to the points along the chamber transect. A basic description of the vegetation in the quadrat was recorded at each point.

### 3.7 Hydrology

In the winter, before the 2006 growing season, three PVC wells were installed. A frozen soil core was extracted (about a meter length) and a PVC tube, 5 cm's in diameter, was installed. The PVC tube had an open ended bottom and perforations throughout the bottom 50 cm's. A mesh stocking covered the bottom and perforations to allow water in and keep soil out. The three wells were located along a transect starting at the edge of the riparian zone and ending in the cropped upland. Well 1 was located at the wetland fringe at the cattail and sedge interface. Well 2 was located at the midslope position (at the edge of the cropped upland and riparian zone). Well 3 was located in the cropped upland. Unfortunately the third well was not long enough to reach the water table, at this location and the well remained dry all year. Wells 1 and 2 were sampled on a weekly basis using a blow-pipe (a meter stick with tubing attached creating one open end at the bottom and one open end at the top, which was accessible to blow into). Air was blown into the tube as the meterstick was lowered into the well. Bubbles were heard when the bottom of the meterstick reached the water, and the depth was recorded. Both wells eventually dried up by August 11$^{th}$, 2006.

The water level of the pond was recorded at the scaffold on a weekly basis. This was done using a meter stick with a basket attached to the bottom, which would ensure that the stick was not inserted into the sediment. Measurements were taken at the same location every week to ensure that the unevenness of the bottom sediment would not contribute any error to the water depth measurements.

### 3.8 The eddy correlation system and basic meteorological data

#### 3.8.1 Basic meteorological data

Low frequency meteorological data was recoded hourly at a station located on the scaffold in the center of the Deep Crop wetland. Low frequency parameters included net solar radiation, wind speed, panel temperature, relative humidity, surface water temperature, and integrated sediment depth temperatures (recorded at 5 cm, 25 cm, 45 cm, 75 cm and 110 cm below the sediment).

#### 3.8.2 Eddy correlation data

An eddy correlation system was set up at the Deep Crop Wetland and was in operation for both the 2005 and 2006 growing season. The objective of the eddy correlation system is to sample the concentration of a trace gas (in this case $CO_2$) in the turbulent parcels of air at the boundary layer and to determine the net difference crossing the integrated canopy/water-atmosphere interface (Baldocchi, 2003). A flux is calculated by statistically analyzing the instantaneous vertical mass flux density according to the rules of Reynolds decomposition (Baldocchi, 2003, Reynolds, 1895).

The eddy correlation system was located at the scaffold in the center of the Deep Crop wetland. This system included an ultrasonic anemometer (Model 81000, R. M. Young Company, Michigan, U.S.A.) which provided information on 3D wind velocities and an open path infrared gas analyzer (Li-7500, LI-COR, Lincoln, NE) which provided information on gas concentrations ($CO_2$ and $H_2O$). In order to capture the small eddies which occur close to the surface both instruments operate at a high temporal frequency, and have the ability to quickly record large amounts of data.

The height at which the anemometer is set above the surface will determine the flux footprint. The 'flux footprint' or 'fetch' is the area upwind of the anemometer that is contributing to the flux measurements (Figure 3.8). There is a simple rule of thumb which states that for every meter above the surface, the anemometer flux footprint encompasses an area 100 meters upwind

(Moncrieff et al. 1997). The section of land upwind of the anemometer is generally to the north and therefore obstructive equipment capable of impairing the fluxes were installed to the south of the anemometer. Therefore all fluxes with southerly winds were removed from the final data set. The anemometer was placed approximately 1 – 1.5 meters above the surface of the water (considering that the water fluctuates up to ½ of a meter during the growing season). The flux footprint was therefore 100 – 150 meters upwind of the scaffold. The fetch includes the open water, the cattail zone, the sedge and grass zone, and the cropped upland.

The data set produced from this instrument had errors associated with it, which included missing data (due to power problems) and outliers. Outliers were determined using an interquartile range computation. No gap filling was used for this data set as the useable data gave a good enough representation of the data needed for the objectives of this study. In this case the periods of missing data are simply absent from the seasonal data set. The data set was plotted on a weekly basis and any obvious outliers were eliminated. Only full days were used, the partial days were eliminated.

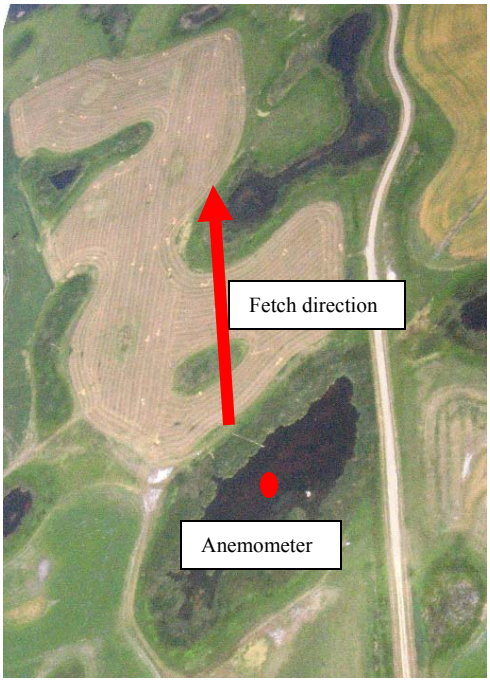


Figure 3.8 Areal photo of the Deep Crop Wetland showing the location of the eddy correlation system and direction of the flux footprint

### 3.9 Continuous $CO_2$ sampler

A continuous aquatic carbon dioxide sampler (CACS) was located at the scaffold in the center of the Deep Crop wetland for determination of continuous fluxes of $CO_2$ at the air-water interface of the pond. This piece of equipment consisted of a 10X datalogger (Campbell Scientific, Edmonton, Canada), a LI-820 $CO_2$ analyzer (LI-COR, Lincoln, NE) and a Mini-module membrane contactor (Membrana, Charlotte, NC). The CACS recorded concentrations of $CO_2$ in the atmosphere and water every hour, along with other environmental variables needed to calculate a flux such as water and air temperature, barometric pressure, and the temperature of the CR10X. This unit operated by first drawing ambient air into the $CO_2$ analyzer, and recording the concentration. After the atmospheric $CO_2$ concentration is measured the CACS begins pumping water (from 2-5 cm below the surface) through the mini-module which allows the $CO_2$ from the water to penetrate the membrane of the mini-module and enter the IRGA. This is done for 15 minutes to allow time for the gases to equilibrate, at which point the $CO_2$ concentration is recorded. A copy of the CACS program is located in Appendix A. Fluxes were calculated using the difference in the partial pressure of $CO_2$ in the atmosphere and water along with a solubility coefficient and transfer velocity (Equation 3.2). The transfer coefficient used for these calculations was derived by MacIntyre et al. (1995), from a least squares power law fit through the results of 5 lakes experiments using tracers. The experimental lakes ranged in size from 0.13 $km^2$ to 500 $km^2$ and encompassed a temperature range of 4 - 23°C and salinities as high as 73% (Equation 3.3). In this equation k(600) refers to the normalization of k to $CO_2$ at 20°C. The empirically derided solubility coefficient was taken from Weiss (1974). Windspeed at a height of 10 m above the waters surface is needed for determination of the transfer velocity and was calculated using an equation from Stull (1988) (Equation 3.5). A temperature correction was done to account for the difference in equilibrator temperature and in-situ temperature (derived by Goyet et al. 1993).

$$F=k*\alpha\ (\Delta\rho CO_2) \qquad (3.2)$$

Equation 3.2 Water-atmosphere carbon dioxide flux equation (MacIntyre et al., 1995)

$$k(600) = .45u_{10}^{1.6}(Sc/600)^{-0.5} \quad (3.3)$$

Equation 3.3 Transfer velocity (MacIntyre et al., 1995)
Where $u_{10}$ is the windspeed at 10 m above the water surface and Sc is the Schmidt number

$$\ln\alpha = A1+A2(100/Ts)+A3(Ts/100)+\sigma(B1+B2(Ts/100)+B3(Ts/100)^2) \quad (3.4)$$

Equation 3.4 Solubility coefficient (Weiss, 1974)
Where σ is the salinity in parts per thousand, Ts is the surface water temperature in °K, A1 is -58.0931, A2 is 90.5069, A3 is 22.2940, B1 is 0.027766, B2 is -0.02588, and B3 is 0.0050578. This equation represents solubility as mol/kg/atm

$$U(z)=(u^*/k)\ln(z/z_0) \quad (3.5)$$

Equation 3.5 Equation for the determination of windspeed (Stull, 1988)
Where u* is the friction velocity, Z is the height of anemometer above water surface, K is .4, and $z_0$ is the roughness length (.005).

$$pCO_2=pCO_2^*(\exp(0.0423(Tis-Teq))) \quad (3.6)$$

Equation 3.7 Equation for $pCO_2$ temperature correction (Goyet et al. 1993)
Where $pCO_2$* is the measured $pCO_2$, Tis is the in-situ temperature, and Teq is the equilibrator temperature

### 3.10 Statistical analysis

Statistical analysis was completed using SPSS (ver. 14.0). To test for differences within and between landscape positions on $CO_2$ fluxes (from the small soil respiration chambers) a repeated measures test was used (p=0.05). This is done for both 2005 and 2006. An analysis of variance (ANOVA) was used to test for significant differences within and between landscape positions for the large chambers. ANOVA was also used to test for differences in epiphyton chlorophyll-*a* concentrations between years and between water column depths. Spearman rank correlation analysis was used to determine if relationships exist between $CO_2$ flux from the pond and water chemistry parameters as well as atmospheric conditions.

# 4.0 RESULTS AND DISCUSSION: AQUATIC $CO_2$ EXCHANGE AND ASSOCIATED ELEMENTS

## 4.1 General Meteorology

The average monthly temperatures for 2006 were slightly warmer than 2005 from April to August and almost identical in September (figure 4.1a). Average monthly net radiation was also greater in 2006 (Figure 4.1b). Both years had higher than average April temperatures (6.5°C and 8.2°C for 2005 and 2006, respectively) relative to the climate normal for Brandon (3.6°C is the climate normal for April), but fell within 2°C of the climate normal for the rest of the growing season. Surface water and air temperature followed a similar seasonal pattern for both growing seasons (Figure 4.2). On average air temperature was slightly cooler than the surface water temperature. The average monthly windspeed was similar for June to September in 2005 and 2006 (Figure 4.1b). Windspeed is an important variable as the $CO_2$ exchange at the water-atmosphere interface of the pond it dependent upon it.

Both 2005 and 2006 had diverse seasonal precipitation patterns across the study period (Figure 4.1a). Precipitation throughout the 2006 growing season was relatively similar to the climate normal; except for July, which was exceptionally dry. This lack of precipitation caused a sharp drop in the water table level at the beginning of the month (Figure 4.3). A slight increase in precipitation in mid-July was followed by a continual decrease until the end of September. Total precipitation for the month of July in 2006 at the Brandon airport was 7.8 mm. This is especially dry considering that the climate normal for this area is almost ten times that amount (75.8 mm) (Environment Canada, 2007). This lack of precipitation combined with above average temperatures, created arid conditions for the month of July, which may have impacted the general functioning of the wetland ecosystem.

Compared to the climate normal, 2005 had less total monthly precipitation in April, August and September, and similar total monthly precipitation in May. June, on the other hand, had three times the total monthly precipitation of the climate normal and July had almost double that amount. The water level in the pond during 2005 experienced large fluctuations from June

(when measurements began) to mid-August at which point there was a sharp drop in water levels (Figure 4.3).

Although 2005 had more precipitation than 2006 during the green period (May, June, July and August), it had less precipitation during the pre-green and post-green periods (April and September). Over the 2005 measurement period, the pond water levels were higher, and appeared to oscillate around the seasonal trend much more than in 2006. The 2006 water levels also showed a late-summer decrease earlier in the season relative to 2005 water levels.

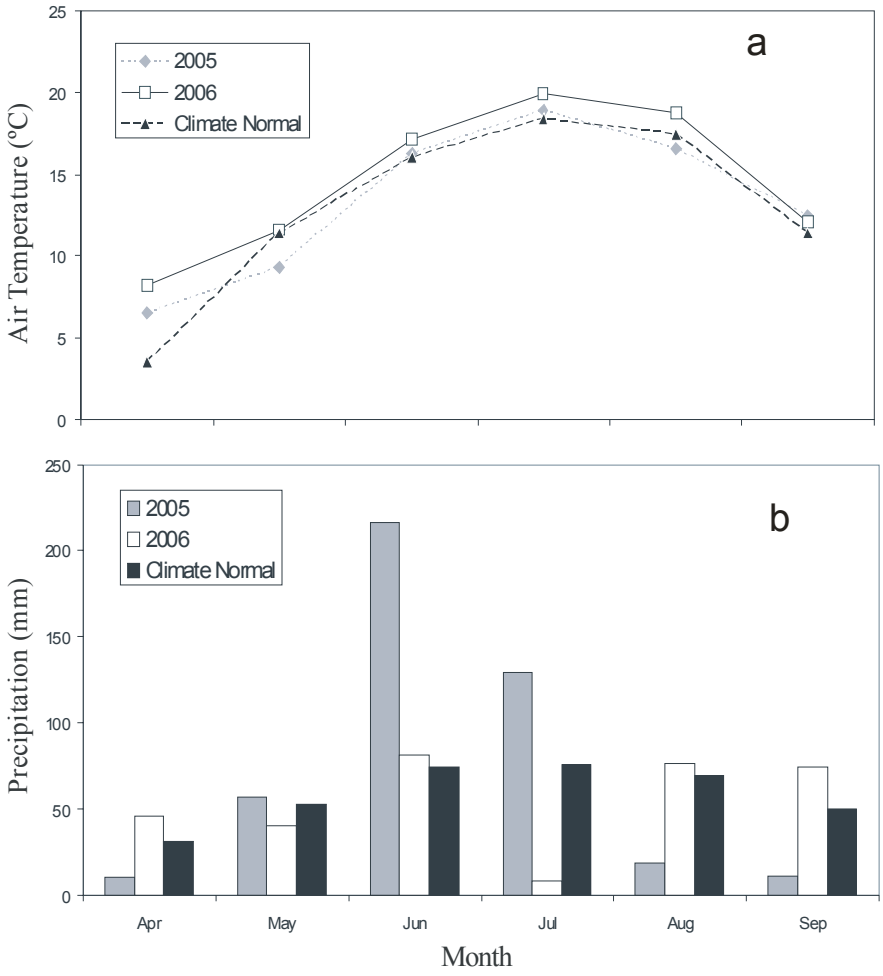


Figure 4.1a Mean monthly (a) temperature and (b) total precipitation for the 2005, 2006 and the climate normal

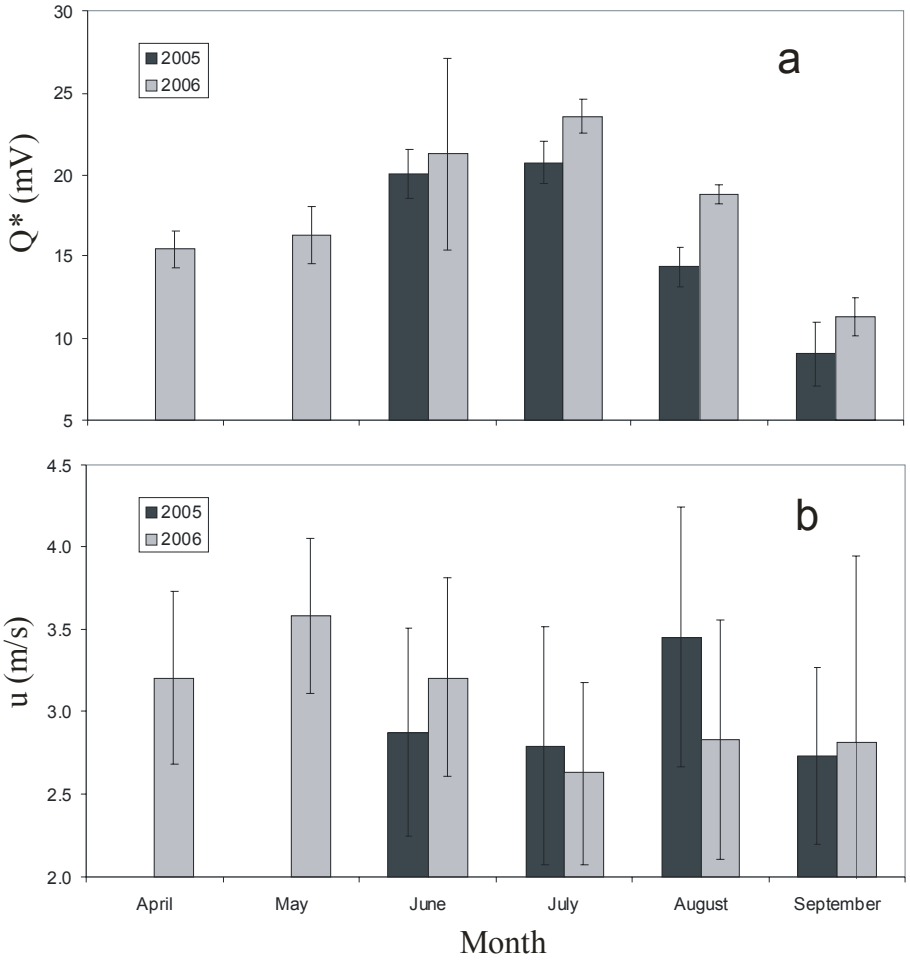


Figure 4.1b Mean monthly (a) net radiation (as represented by Q* which is measured in millevolts) and (b) windspeed (as represented by u and measured in meters per second) for the 2005 and 2006 growing season. Error bars represent standard error

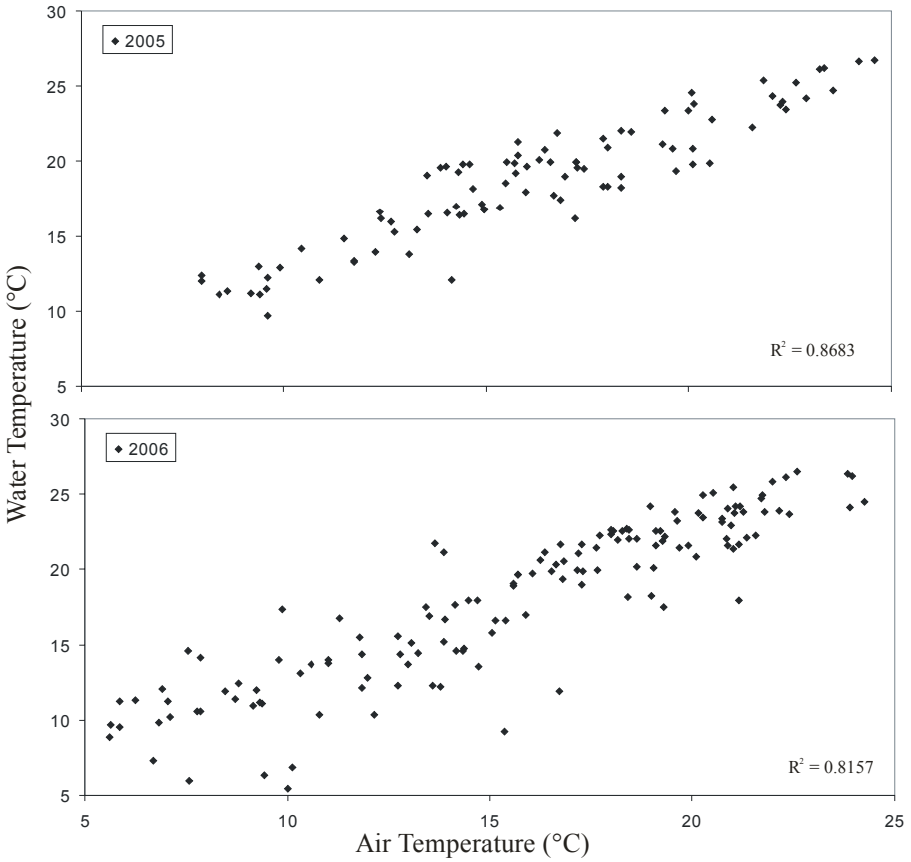


Figure 4.2 Average daily air and water temperature for 2005 and 2006

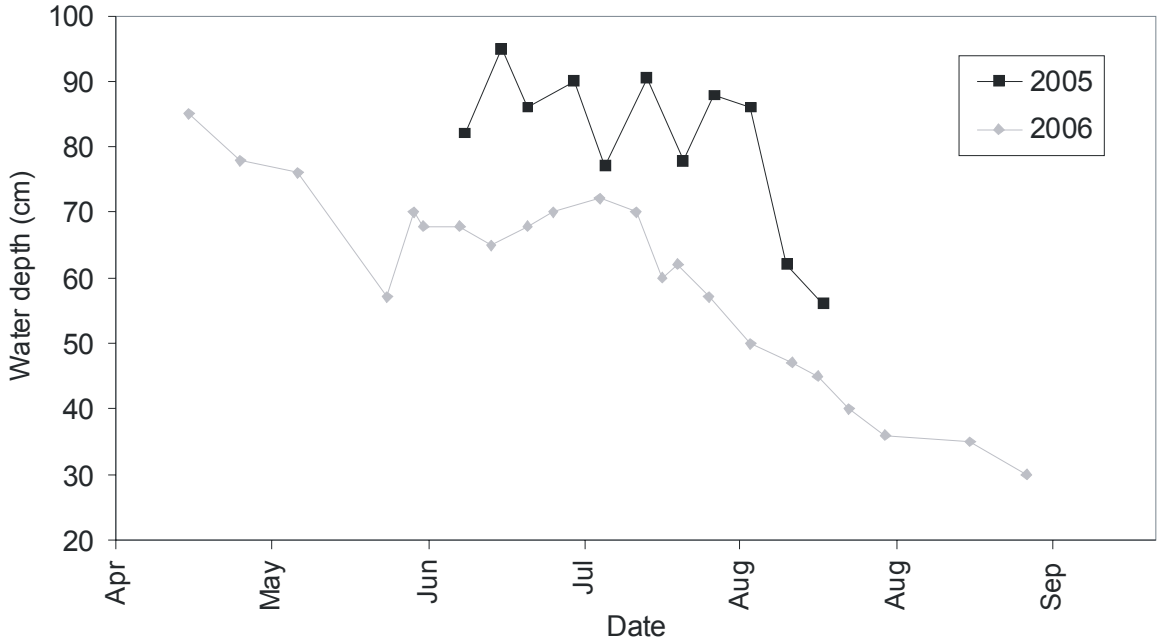


Figure 4.3 Pond water depth as measured throughout the 2005 and 2006 growing seasons

## 4.2 Pond Biomass

### 4.2.1 Algae

Three algal assemblages were measured on a weekly basis throughout the 2005 and 2006 growing season. Measurements from 2005 are from Phipps (2006). These assemblages included epiphyton, phytoplankton, and metaphyton. Epiphyton and phytoplankton were sampled and measured for chlorophyll-*a*. In 2006, metaphyton was calculated as a dry mass and converted to chlorophyll-*a*, while in 2005, metaphyton was calculated directly as chlorophyll-*a*. The difference between the two methods is described in Section 3.

In 2005 the epiphytic chlorophyll-*a* concentrations in the water were greater than in 2006 (Figures 4.5a and 4.5b). In 2005 mean weekly epiphytic chlorophyll-*a* concentrations tended to increase throughout the summer (Figure 4.5a). This is a reasonable epiphyton chlorophyll-*a* trend, as epiphyton colonization commences with installation of the epiphyton rods at the beginning of the season and cumulatively increases as the season progresses. The levels of chlorophyll-*a* found in the pond in 2005 appear to be relatively high in comparison to other studies in prairie wetlands (Robinson et al. 1997 and McDougal, 2001).The chlorophyll-*a* concentration in the mid-water column increased until August. The mid-water column contained higher chlorophyll-*a* concentrations than the other water column depths for the months of July and August, and lower concentrations in September. There was no significant difference the three water level depths epiphytic chlorophyll-*a* concentrations ($p=0.05$) in 2005.

The epiphyton chlorophyll-*a* concentrations were relatively low at the beginning of the 2006 season, but increased in early July (Figure 4.5b). This moderate level of chlorophyll-*a* was sustained until the end of August when the chlorophyll-*a* concentration decreased. The levels of chlorophyll-*a* found in the pond in 2006 appear to be similar to other studies in prairie wetlands (Robinson et al. 1997 and McDougal, 2001). The location of epiphyton in the water column was unevenly distributed, with the majority of chlorophyll-*a* occurring in the upper portion of the water column (Figure 4.4b). There was, however, a period from late July to early August chlorophyll-*a* in the upper water column decreased and chlorophyll-*a* in the middle and lower water column increased (Figure 4.4b). This is likely because the decrease in the occurrence of metaphyton during this time (Figure 4.8) allowed light penetration to the lower water column,

which resulted in an increase in chlorophyll-*a* concentrations in the lower segment of the water column. There was a significant difference in the three water level depths epiphyton chlorophyll-*a* concentrations (p=0.05) in 2006.

This difference in epiphyton chlorophyll-*a* concentrations between years is not uncommon for prairie pothole wetlands, and may be due to a number of environmental and human induced factors. Epiphyton chlorophyll-*a* concentrations may have been affected by the lack of precipitation in July, and an associated shortage of nutrients that would otherwise be introduced to the pond *via* leaching or surface runoff (although nutrient results show no lack of nutrient availability, Table 4.4 and low epiphyton chlorophyll-*a* levels were present before the dry period in July). The overall magnitude may be different between years because of differences in chlorophyll-*a* analysis techniques (see Section 3.5). The seasonal pattern displayed in 2006 may also be due to influx of herbicide from the surrounding farmers fields, which would have inhibited algal growth. Although no information is available about pesticide and herbicide concentrations in the wetland, there is anecdotal evidence that pesticide spraying nearby may have caused these chemicals to enter the pond. Another factor which may have contributed to the lower algal chlorophyll-*a* concentrations in 2006 is the higher dissolved organic carbon concentration in the pond (Table 4.3) which likely limited light penetration necessary for algal production (Jackson and Hecky, 1980, Kalff, 2002 and Badiou, 2005).

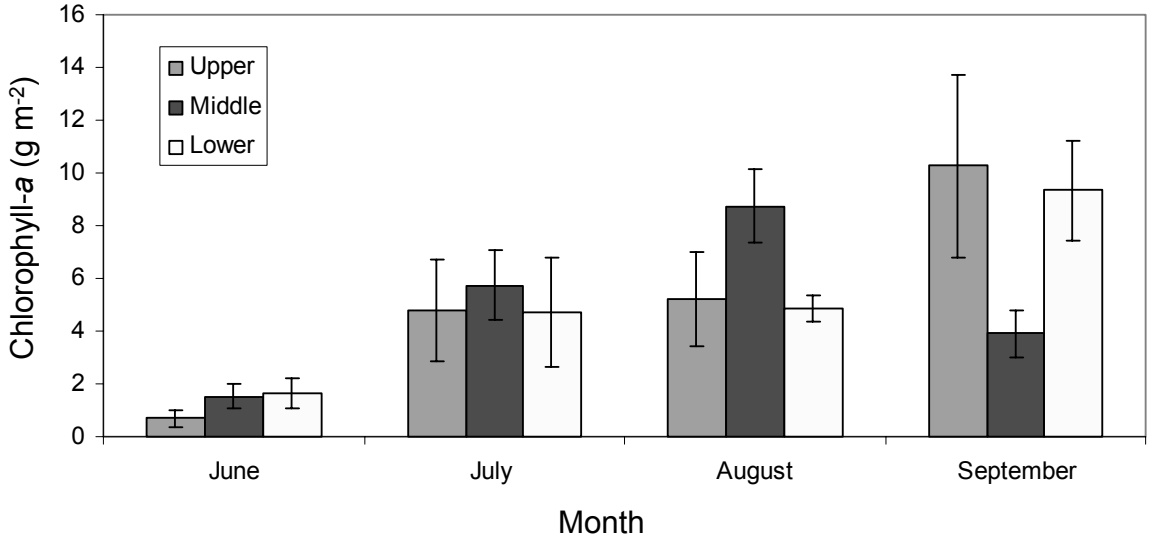


Figure 4.4a Mean monthly epiphyton chlorophyll-*a* concentrations per depth in the water column (2005). Data are from Phipps (2006)

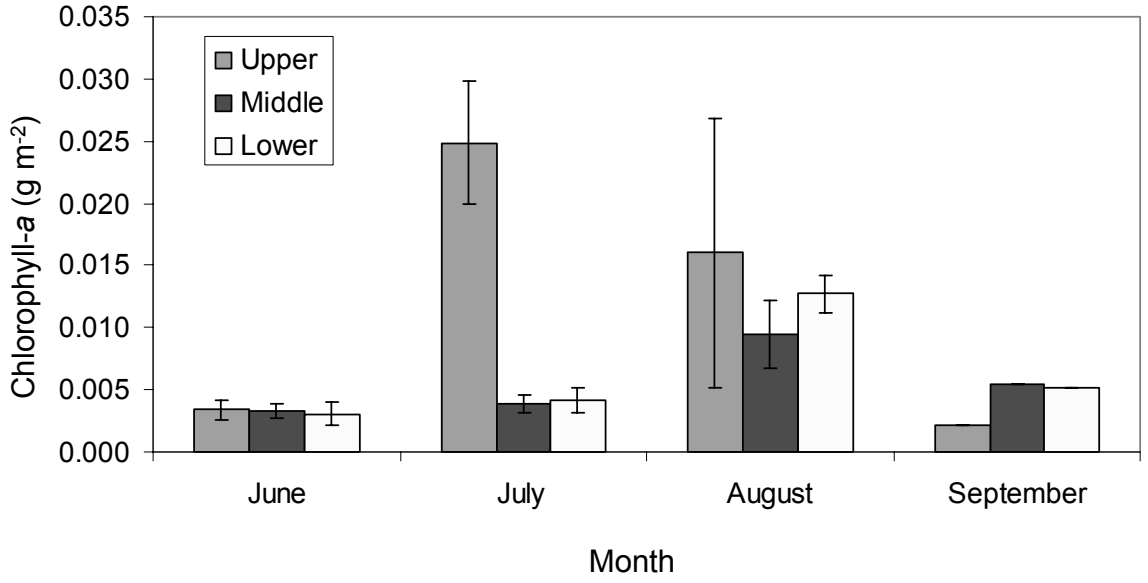


Figure 4.4b Mean monthly epiphyton chlorophyll-*a* concentrations per depth in the water column (2006)

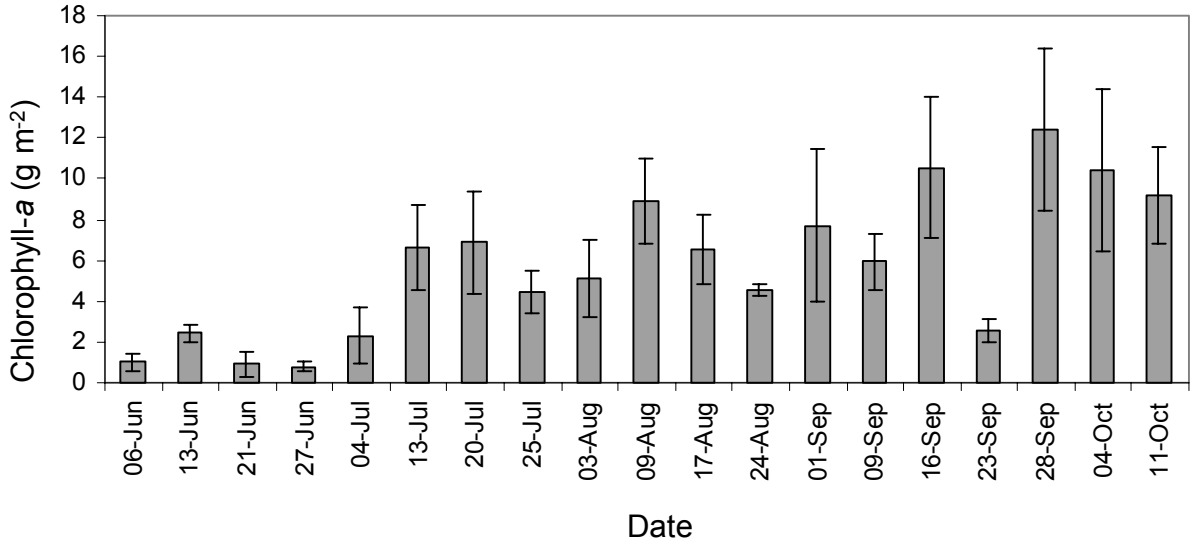


Figure 4.5a Depth-averaged weekly epiphyton chlorophyll-*a* concentrations over the 2005 growing season, error bars represent standard error. Data are from Phipps (2006)

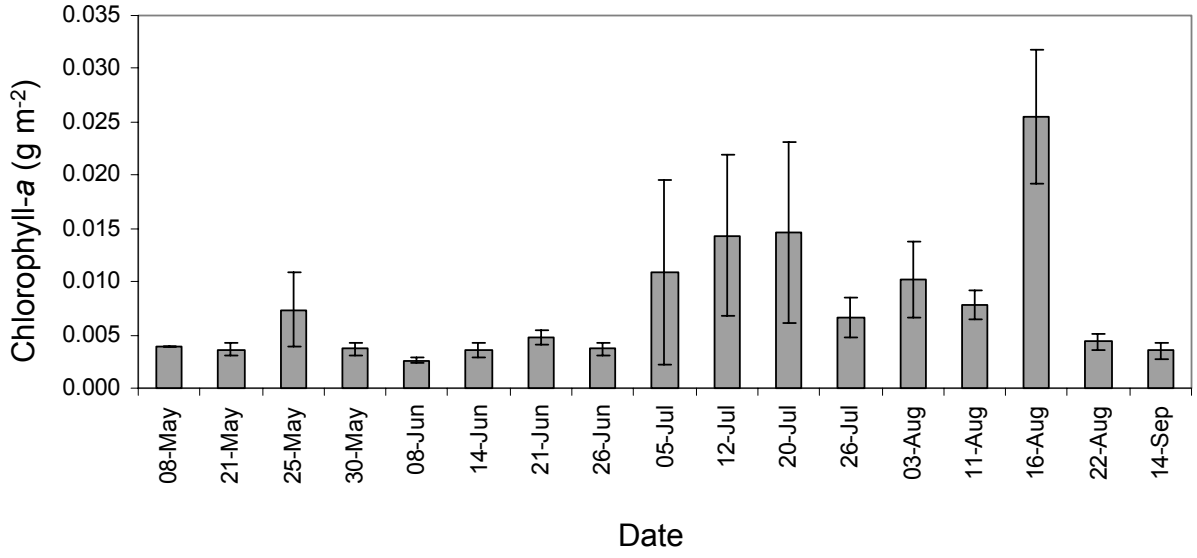


Figure 4.5b Depth-averaged weekly epiphyton chlorophyll-*a* concentrations over the 2006 growing season, error bars represent standard error

The chlorophyll-*a* concentration of phytoplankton in the water column in 2005 was greater than in 2006 for the months of August and September (Figure 4.6). The preceding months from May to July, however, were not significantly different (p=0.05). The magnitude of chlorophyll-*a* over both years is reasonable for wetlands in this are and has been known to fluctuate 150 μg $L^{-1}$ in a growing season (McDougal, 2001). The general seasonal trend in phytoplankton chlorophyll-*a* concentrations was different between years. In 2005 phytoplankton chlorophyll-*a* increased throughout the season and peaked in September, where as 2005 concentrations increased slightly from May to June and decreased thereafter. The sharp increase in chlorophyll-*a* in August of 2005 occurs at the same time as a sharp increase in dissolved organic carbon (Table 4.3) This combination of events may have occurred because of the senescence in the pond, and drop in water level (largely metaphyton, submersed macrophyte and emergent macrophyte senescence) which would have increased dissolved organic matter as well as provided nutrients for algal growth. As was the case for epiphyton, the difference in chlorophyll-*a* concentrations between years is not abnormal for prairie wetlands.

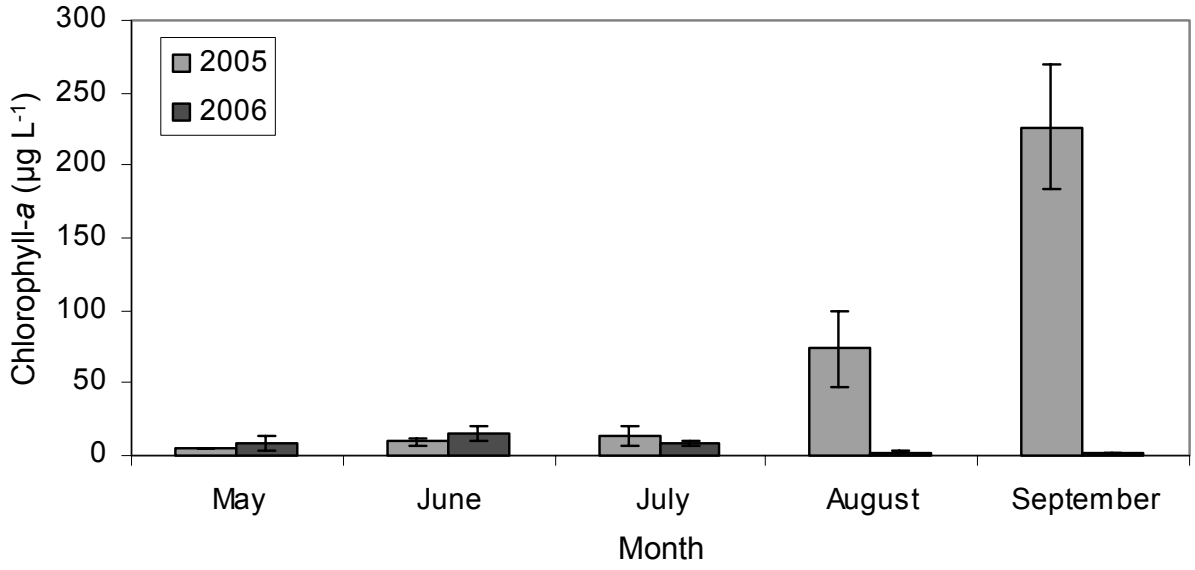


Figure 4.6 Average monthly phytoplankton chlorophyll-*a* concentrations for the 2005 and 2006 growing season (2005 data from Phipps, 2006)

Metaphyton chlorophyll-*a* concentrations were highly variable throughout the 2005 growing season (Figure 4.7). Metaphyton chlorophyll-*a* concentrations peaked in late August, decreased dramatically for the month of September, and then increased again in October, when a new form of metaphyton presented itself. The magnitude of metaphyton chlorophyll-*a* in the pond over the 2005 growing season was much greater than metaphyton chlorophyll-*a* values reported in the literature (Robinson et al. 1997 and McDougal, 2001). The 2006 seasonal metaphyton chlorophyll-*a* curve was similar to that of phytoplankton (Figure 4.6 and 4.7), with peak concentrations occurring in late June to early July and decreasing thereafter. The two years were similar in that many of the August and September samples had no metaphyton present at all.

It must be noted, however, that due to the nature of the metaphyhton sampling technique, the data collected are not representative of the whole pond. Metaphyton formation usually occurs in a band around the periphery of the pond and without information of the area that the metaphyton cover it is difficult to compare metaphyton biomass from year to year (as the percent cover may change). In addition error associated with sampling techniques (different sampling techniques used between years and thus conversions were made, more information is available in Chapter 3) may also have contributed to the difference between years.

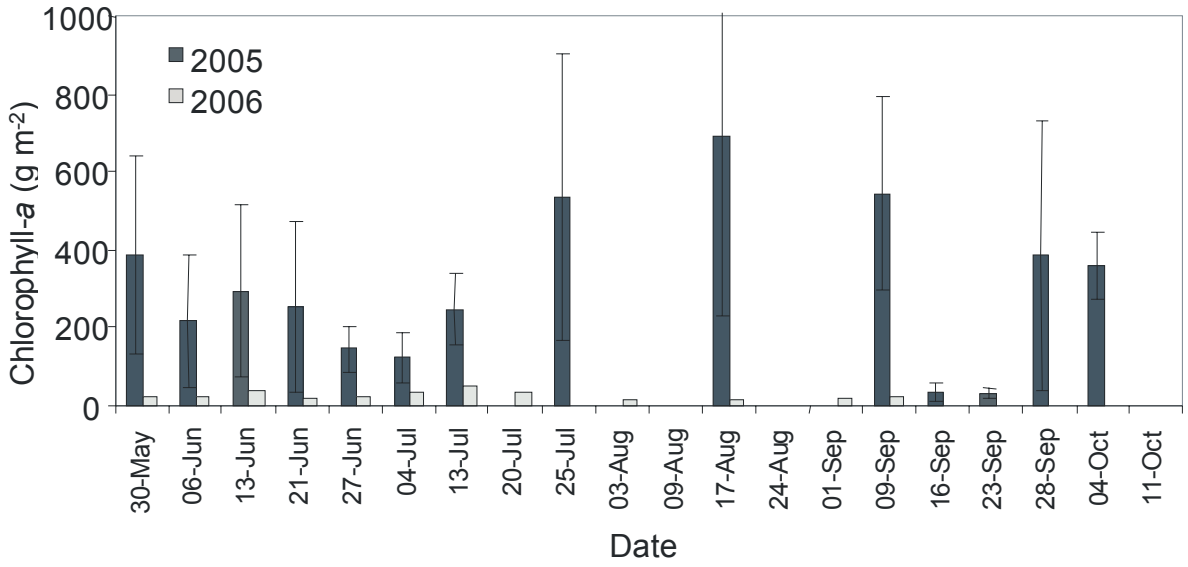


Figure 4.7 Metaphyton chlorophyll-*a* for 2005 and 2006, error bars represent standard error (2005 data from Phipps, 2006)

The three algal assemblages measured in the pond, tended to have lower chlorophyll-*a* concentrations in 2006 than in 2005. As mentioned above this is not uncommon of prairie wetlands as they are extremely vulnerable to environmental perturbations. The hydrology and water chemistry of the wetland as well as environmental factors (such as temperature and precipitation) can greatly influence the general functioning of the wetland ecosystem and can impact the productivity of the various algal assemblages.

There is anecdotal evidence supporting the hypothesis that pesticides entered the pond in 2005 and may have influenced the chlorophyll-*a* concentrations of the three algal assemblages. An influx of herbicide into the pond prior to, or just after seeding may have acted as an algal suppressant. In addition to chemical inputs, the climatic conditions during the summer of 2006 (such as the dry period in July) may have also inhibited algal growth by limiting the influx of nutrients and decreasing water levels. The higher dissolved organic carbon concentrations in the pond in 2006 may have limited light penetration and thus algal growth (Jackson and Hecky, 1980; Kalff, 2002 and Badiou, 2005). Another cause of the low algal chlorophyll-*a* concentrations in 2006 may be due to algal parasitism or disease. Although overlooked by many

limnologists as a cause of loss, these viruses, lysing bacteria, parasitic protozoa and fungal parasites can greatly impact algal community abundance (Kalff, 2002).

In general there appeared to be a decrease in chlorophyll-*a* concentrations from the three algal assemblages after the dry month of July in 2006. Epiphyton decreased with exception of sampling date in mid-August (Figure 4.5). Metaphyton was sparsely present between late-July and early-September at which point a new form of metaphyon presented itself, and phytoplankton gradually decreased after peaking in June.

### 4.2.2 Macrophytes

Both years had similar aboveground-emergent macrophyte biomass (AEMB). Aboveground refers to the portion of the vegetation above the sediment surface and does not include the roots. AEMB in the Low Prairie zone was significantly greater ($p=0.05$) in 2005 than 2006. However, there was no significant difference ($p=0.05$) in AEMB in the Deep Marsh zone between years. The AEMB observed within our pond, is similar to findings from other studies from or near the Prairie Pothole Region (Table 4.1), with the noted exception of the MERP experiment at Delta Marsh, Manitoba (van der Valk, 2000) and the St. Denise site in Saskatchewan (Phipps, 2006). Delta Marsh, however, is a very different system as it is not a closed basin wetland. This larger-scale wetland is influenced by the adjacent lake, and therefore differing results relating to hydrology should be expected.

The aboveground-submerged macrophyte biomass (ASMB) present in 2005 was significantly greater ($p=0.05$) than in 2006 (Figure 4.8). Although fairly robust, aquatic macrophytes are also influenced by environmental factors and may differ from year to year in Prairie wetlands. The difference among years may have been influenced by allochthonous sources of vegetation inhibitors such as herbicides which can inhibit growth, but as discussed above is based on anecdotal evidence. The reduction in dry weight from 2005 to 2006 may also be due to a decrease in photosynthetic inefficiency. Some submersed macrophytes secrete dissolved organic matter during active photosynthesis, which can greatly reduce its photosynthetic efficiency (Wetzel, 2001).

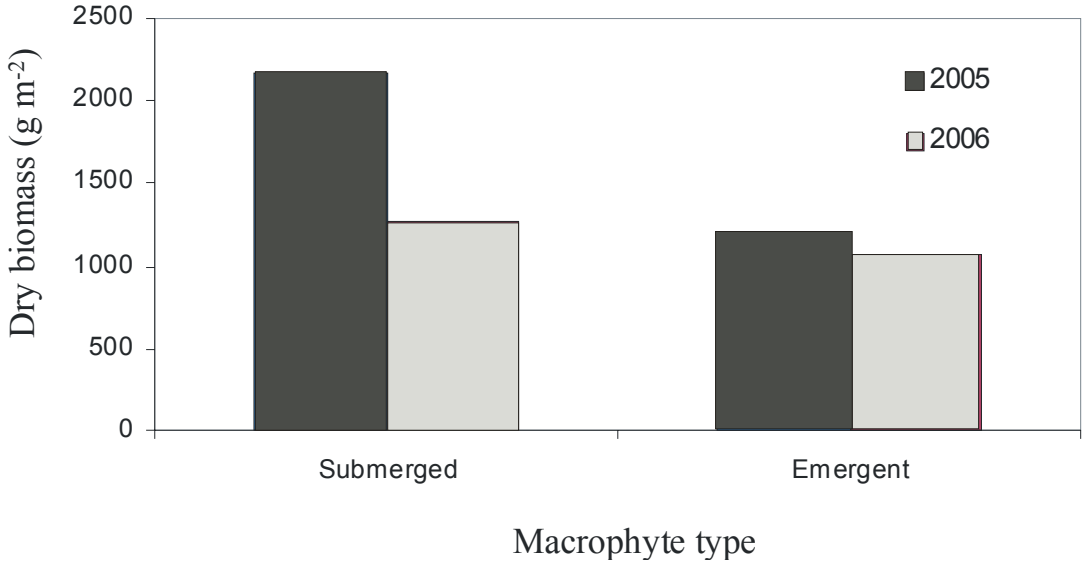


Figure 4.8 Macrophyte dry biomass for 2005 and 2006

Table 4.1 Aboveground biomass estimates for emergent and submersed macrophytes for primarily cattail dominated marshes, located in or near the Prairie Pothole Region (PPR)

| Source | Location | AEMB (g $m^{-2}$) | ASMB (g $m^{-2}$) |
|---|---|---|---|
| This study | PPR, MB | 1072.00 ± 201.4 | 1270 |
| Phipps (2006) | PPR, SK | 111.3 | 85 |
| Phipps (2006) | PPR, MB | 2168 | 1200.2 |
| van der Valk (2000) | PPR, MB | 346** | 0 – 61 |
| Boneville et al. (In Review) | ORV*, ON | 1149 ± 100 | |
| Bray (1962) | PPR, MN | 1360 | |
| Smith et al. (1988) | PPR, WI | 1400 | |
| Dubbe et al. (1988) | PPR, MN | 43 – 2110 | |
| Davis and van der Valk (1983) | PPR, IA | 2000 | |

*Ottawa River Valley (ORV)
**AEMB during the baseline year (does not include water level manipulation measurements)

### 4.3 Water chemistry

Total P and Total N increased throughout both the 2005 and 2006 growing seasons (Table 4.4). According to the Redfield ratio, N:P ratios greater than 16:1 (by atoms) reflects a P limited system (ratios are above the demand ratio for algal production) where as ratios less than 16:1 (by atoms) reflects a N limited system (Redfield et al. 1963). With the exception of May

2005, which was P limited, the Deep Crop wetland stayed close to the Redfield ratio throughout both growing seasons. This indicates that the system was co-limited by N and P. Total P values for the wetland surface water range from 0.07 mg/L to 0.45 mg/L and defined the status of the wetland as highly eutrophic. This is not uncommon for small and shallow lakes (Kalff, 2002). Nitorgen is commonly the first element to be limiting in aquatic systems located in an agricultural setting. Many algae and bacteria assimilate P at rates greater than they are able to grow, sestonic algal production has also been positively correlated with TP (Kalff, 2002). As well as impacting the production of wetlands, eutrophication may also affect trace gas exchange. Etrophication was found to increase emissions of climate-relevant trace gases (Merbach et al., 2002) because of the increased availability of C and N compounds.

DOC and DIC were measured in the Deep Crop wetland in 2006 (Table 4.3), but only DOC was measured in 2005 (Table 4.2). DOC and DIC increased throughout the 2006 growing season. In 2005, the DOC increased from an average of 2.4 ± 0.4 mg/L in May, June and July to 139.7 mg/L for August (Table 4.2). DOC concentrations are an indication of the relationship between DOC producing algae and macrophytes; DOC consuming bacteria; and allochthonous inputs and outputs of DOC. It is likely that the large increase in DOC in August of 2005 was due to a number of factors. Senescence of submersed macrophytes and metaphyton mats as well as a decrease in water level may have contributed to an increase in DOC concentration. External sources such as inputs from the surrounding cultivated lands (inputs would have had to be transported via wind, as no large precipitation events took place during this time), and contributions from the large duck population inhabiting the pond may also have contributed to this increase. Allochthonous inputs have been found to be important contributors to shallow lake organic carbon cycles by contributing 30% to the total annual input (Ramlal et al., 1994). It appears that this high level of DOC was somewhat sustained over the winter and is the reason for the higher DOC levels in the spring of 2006. It is possible that all factors were more equally at play during the 2006 growing season, hence the small observed variation in DOC over the 2006 growing season.

The pH and salinity of the wetland (Figure 4.9) was within the provincial range, which indicates that the values are characteristic of the region. The salinity of the pond increased during the period of pronounced drying in late-July, 2006. It stands to reason that increased

evapotranspiration would favour higher concentration of salts. A seasonal rise in salinity was also observed in 2005, but not to the same extent.

The dissolved oxygen (DO) levels in the pond as shown in Figure 4.9, appear to be very low and may not represent the absolute value (as mentioned in Section 3). The seasonal pattern, however, may be correct. Although 'relatively' large amounts of DO were found in the water in the spring of 2006 (in comparison to DO levels during the growing season), this amount is low considering that many smaller lakes may experience 100% DO saturation during this time due to the lake turnover (Wetzel, 2001). Low DO levels, relative to what might be expected in an idealized lake, occur near the surface where large amounts of DOM are available, an example of an ecosystem which commonly experiences low DO levels is a dystrophic bog (Wetzel, 2001).

In 2006 the DO in the water column decreased by late-June to levels that were consistent to the end of the summer. In 2005, on the other hand, both large and small amounts of DO were observed throughout the green period. The 'relatively' high and low oxygen content of the pond during the growing season of 2005 is likely due to the cyclic nature of algal turnover. The higher DO levels indicate higher algal production, and the lower levels may have been produced by algal or organic matter decomposition. Algal decomposition occurs regularly, due to the fact that algal turnover can be as short as a couple of days.

Dissolved oxygen concentrations in wetlands often exhibit pronounced diurnal changes, these diurnal fluctuations inversely correspond with $CO_2$ concentrations in the water. Although exceptionally high night-time respiration rates are common in wetlands and often produce near anoxic levels (Kalff, 2002), an increase in DO is often common during daytime hours and does not explain the near anoxic daily averages experienced in the pond both in 2005 and 2006. The reduced wind-induced turbulence effecting Prairie pothole wetlands, because of the dense ring of emergent macrophytes surrounding the pond and percent cover of submersed macrophytes, can greatly limit DO inputs from the atmosphere (Kalff, 2002). Conversely submersed macrophyte production can increase DO during the day through production.

The high pH at the beginning of the 2006 growing season corresponded with the algal and plant production in the wetland. During this time, carbohydrates and oxygen were produced from dissolved carbon dioxide. A decrease in dissolved carbon dioxide will increase the pH of the system. This also translates into a diurnal cycle where high $CO_2$ levels in the morning (due to respiration during the night) will yield a low pH, and higher dissolved oxygen levels during the

day will yield a higher pH. Thus the seasonal trend of higher pH levels in May tapering off until mid-June (where it maintains its level) is also seen in the DO and oxidation-reduction potential (ORP) graphs for 2006. The pH values for summer of 2005 were also noticeably higher than for 2006. This is expected because production is perceived to be greater in 2005 than in 2006. Dissolved $CO_2$ levels are reviewed in Section 4.4.

Table 4.2 Dissolved organic carbon concentrations for 2005

| ***Date*** | ***DOC*** *mg/L* |
|---|---|
| *May* | *2.4* |
| *Jun* | *2.7* |
| *Jul* | *1.9* |
| *Aug* | *139.6* |

Table 4.3 Dissolved organic carbon and inorganic carbon concentrations for 2006

| ***Date*** | ***DOC*** mg/L | ***DIC*** *mg/L* |
|---|---|---|
| *May* | *30.1* | *59.0* |
| *Jun* | *43.6* | *70.3* |
| *Aug* | *51.6* | *79.5* |

Table 4.4 Total phosphorus, total nitrogen and N:P ratios for 2005 and 2006

| Date | Total Phosphorus (mg/L) | Total Nitrogen (mg/L) | N:P (moles) |
|---|---|---|---|
| 2005 | | | |
| 11-May-05 | 0.07 | 1.54 | 47.96 |
| 06-Jul-05 | 0.32 | 2.41 | 16.92 |
| 24-Aug-05 | 0.45 | 2.72 | 13.40 |
| 2006 | | | |
| 03-May-06 | 0.24 | 1.71 | 15.64 |
| 27-Jun-06 | 0.37 | 2.41 | 14.49 |
| 15-Aug-06 | 0.38 | 3.12 | 18.10 |

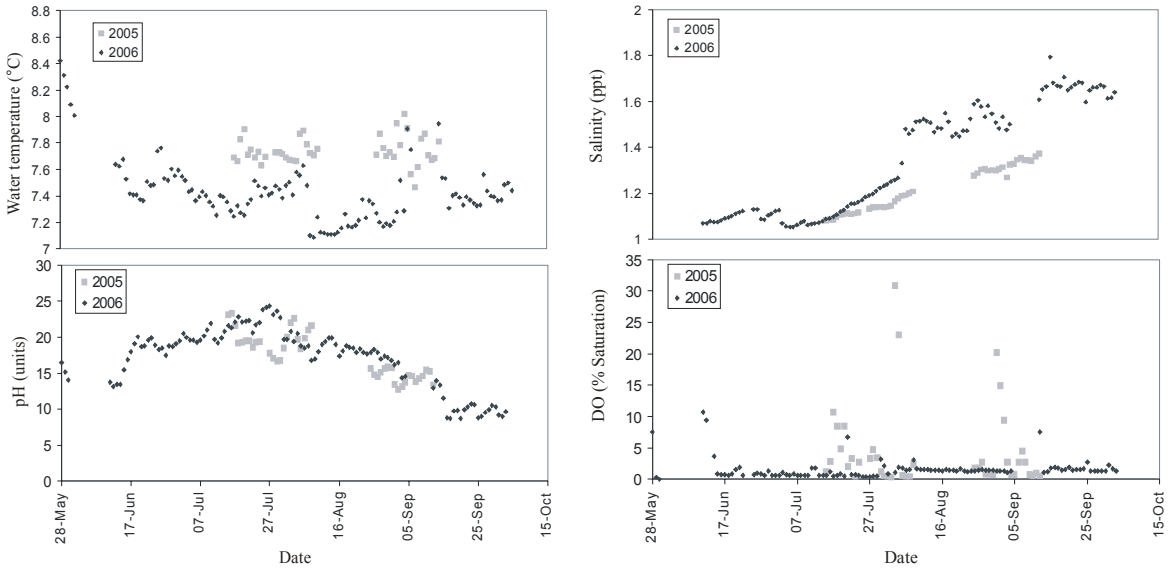


Figure 4.9 2005 and 2006 average daily water chemistry (including water temperature, pH, salinity, and luminescent dissolved oxygen)

## 4.4 Dissolved $CO_2$ and air-water $CO_2$ exchange

Continuous $CO_2$ fluxes from the pond were measured and recorded every hour using a continuous aquatic carbon dioxide sampler or CACS (described in Section 3.9), which was located at a scaffold in the center of the pond. The data collected over both summers were not

continuous and were interrupted because of logistical issues associated with the continuous unattended operation of the sensor. However, four near continuous periods of measurement are available during the 2006 growing season, and three periods throughout the 2005 growing season.

In 2005, measurement periods consisted of July 1st to July 6th (period I); July 14th to July 21st (period II); and September 21st to September 28th (period III). In 2006 the four periods were: June 14th to June 21st (period I); July 21st to July 30th (period II); August 1st to August 16th (period III); and September 28th to October 17th (period IV).

### 4.4.1 $pCO_2$ and $\Delta Pco_2$

In 2005 $pCO_2$ concentrations in the water ranged from 301 μatm $atm^{-1}$ to 1911 μatm $atm^{-1}$ (Figure 4.11a). The two mid-summer sample periods (I and II) had maximum $pCO_2$ levels of 766 μatm $atm^{-1}$. In 2006 $pCO_2$ ranged from 228 μatm $atm^{-1}$ in period IV to 1906 μatm $atm^{-1}$ which was observed multiple times in periods I, II and III. Carbon dioxide concentrations during the green period of 2006 (which consisted of the first three periods) ranged from 347 μatm $atm^{-1}$ to 1938 μatm $atm^{-1}$. During senescence (or IV period) the $CO_2$ concentrations in the water ranged from 2 μatm $atm^{-1}$ to 962 μatm $atm^{-1}$. Seasonal trends from the two years are very different in that 2006 had higher $pCO_2$ levels in the early summer, while in 2005 the seasonally high $pCO_2$ levels were observed from mid to late September (Figure 4.11b).

The difference between the partial pressure of $CO_2$ in the atmosphere ($pCO_{2\,(a)}$) and pond water $pCO_2$ is denoted as $\Delta Pco_2$. The seasonal trend appears to be largely influenced by $pCO_2$, due to the fact that $pCO_{2\,(a)}$ is relatively stable throughout the season with very little diurnal variation. The seasonal pattern of $\Delta Pco_2$ between the years is also very different. In 2005, a small $\Delta Pco_2$ was observed with little diurnal variation throughout the growing season. Larger diurnal variations in $\Delta Pco_2$ were observed in the fall. In 2006, however, a large diurnal variation in $\Delta Pco_2$ was observed throughout the growing season, with smaller diurnal variations in the fall. Unlike 2005, the $\Delta Pco_2$ recorded in 2006 shows a pronounced diurnal cycle until period IV. This pattern gives rise to low emissions or uptake during the day and large emission at night (Figure 4.13b). The large diurnal variation in $pCO_2$ is evidence of the biotic production in the pond.

### 4.4.2 Carbon dioxide fluxes

Carbon dioxide fluxes from the pond can be negative or positive. A positive flux represents an efflux from the pond and a negative flux represents $CO_2$ uptake by the pond. In 2005 periods I and II had relatively similar maximum $CO_2$ efflux magnitudes which were small in comparison to period III (Figure 12a). Based on our measurements, it appears that the pond was a slight source of $CO_2$ throughout the green period, then developed into to a large source during the senescence period (starting in early-September), becoming relatively neutral again by mid-September. The early- and late-July sample periods (periods I and II) had maximum $CO_2$ effluxes of 12.5 mmol $CO_2$ $m^{-2}$ $s^{-1}$ and 15.0 mmol $CO_2$ $m^{-2}$ $s^{-1}$ respectively. Mean daily $CO_2$ flux magnitudes ranged from 0.1 to 2.5 mmol $CO_2$ $m^{-2}$ $d^{-1}$ for period I and -0.3 to 4.3 mmol $CO_2$ $m^{-2}$ $d^{-1}$ for period II (Figure 12a). Period III had a much larger maximum $CO_2$ flux magnitude of 160.2 mmol $CO_2$ $m^{-2}$ $s^{-1}$ and a mean daily $CO_2$ flux of 57.0 to –1.3 mmol $m^{-2}$ $d^{-1}$. Minimum $CO_2$ fluxes across all three sample periods ranged from –12.0 to 4.3 mmol $CO_2$ $m^{-2}$ $s^{-1}$.

A mean diurnal pattern was derived for each of the three sample periods in 2005 (Figure 13a). Period I appears to have a relatively neutral diurnal flux and oscillates between 2.5 and -1.0 mmol $CO_2$ $m^{-2}$ $d^{-1}$ (Figure 13a). There is no obvious diurnal pattern for period II. During this period, dips in the sequence occur at 04:00 h, 10:00 h and 18:00 h. Period III had a diurnal curve with minimum fluxes occurring at 8:00h which gradually increased to a maximum at about 23:00. Although period III had similar minimum (daytime) fluxes as the other two sampling periods, the maximum (nighttime) values were much greater.

According to the 2006 mean daily $CO_2$ fluxes (Figure 12b) the first sample period (late-June) consisted of $CO_2$ fluxes that were much larger than the following three sample periods. Mean daily $CO_2$ fluxes from the pond fluxes ranged from 103.9 mmol $CO_2$ $m^{-2}$ $d^{-1}$ in mid-June to –7.9 mmol $CO_2$ $m^{-2}$ $d^{-1}$ in early October (Figure 12b). In period IV the direction of the flux was reversed and the pond became a carbon sink. From the data collected it appears that the pond acted as a net source of $CO_2$ throughout most of the 2006 growing-season, switching to a net sink in late-August/early-September.

According to the period-mean diurnal patterns for 2006 (Figure 13b), period I had the least $CO_2$ uptake during the day, while period IV had the most. Relatively large minimum (or daytime) fluxes were experienced in period I. Period I also had the largest diurnal variation, with

the $CO_2$ flux maximum and minimum covering a range of about 50 mmol $m^{-2}$ $d^{-1}$. It appears that as the season progresses the maximum uptake or minimum emission occur later on in the day (with the exception that period I and II are relatively the same). The IV sample period has a diurnal pattern that switches from a sink to a source around 22:00h and then back to a sink at around 2:00h.

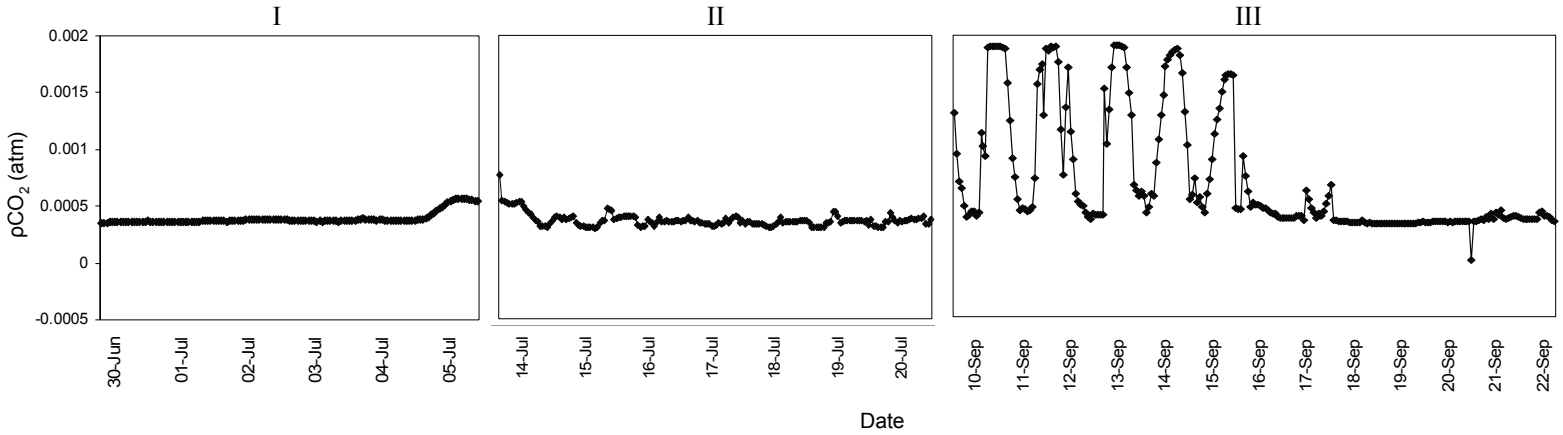


Figure 4.11a Pond water $pCO_2$ in 2005

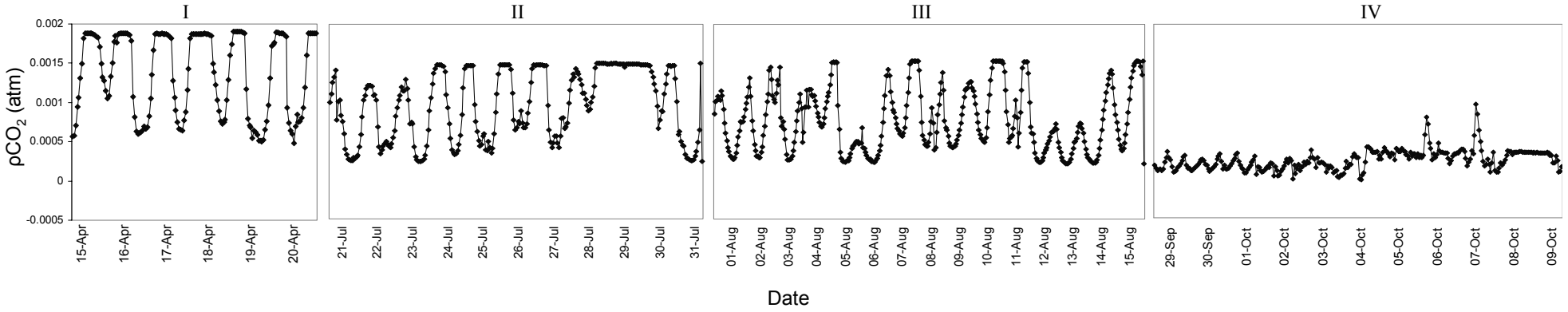


Figure 4.11b Pond water $pCO_2$ in 2006

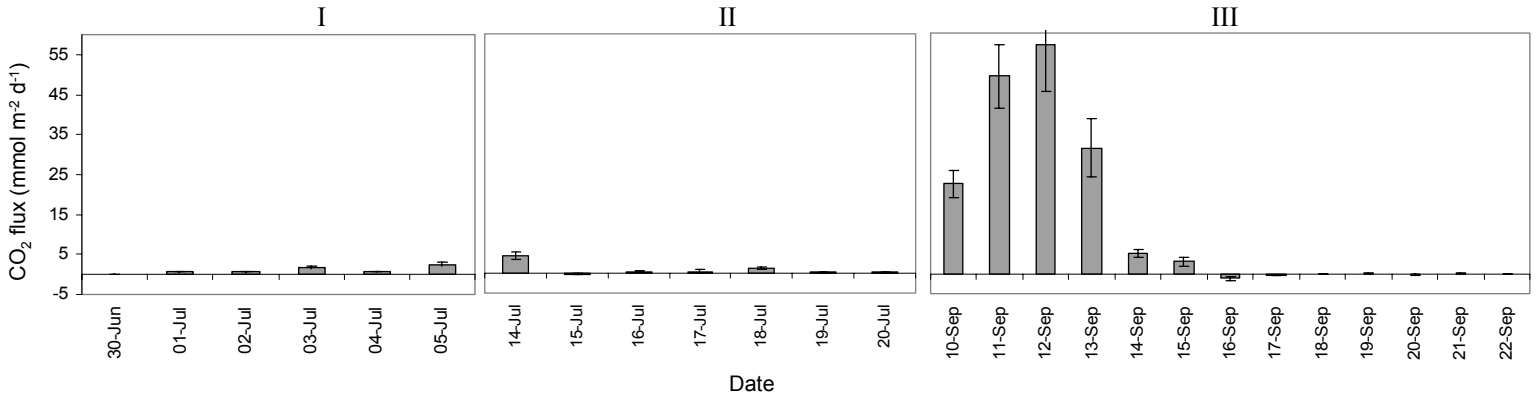


Figure 4.12a Mean daily carbon dioxide flux from the pond in 2005 (error bars represent standard error)

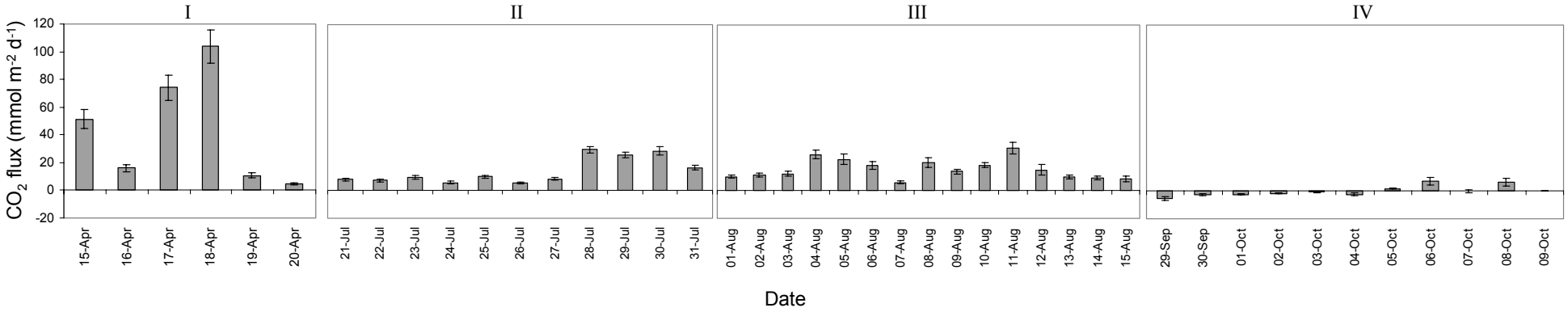


Figure 4.12b Mean daily carbon dioxide flux from the pond in 2006 (error bars represent standard error)

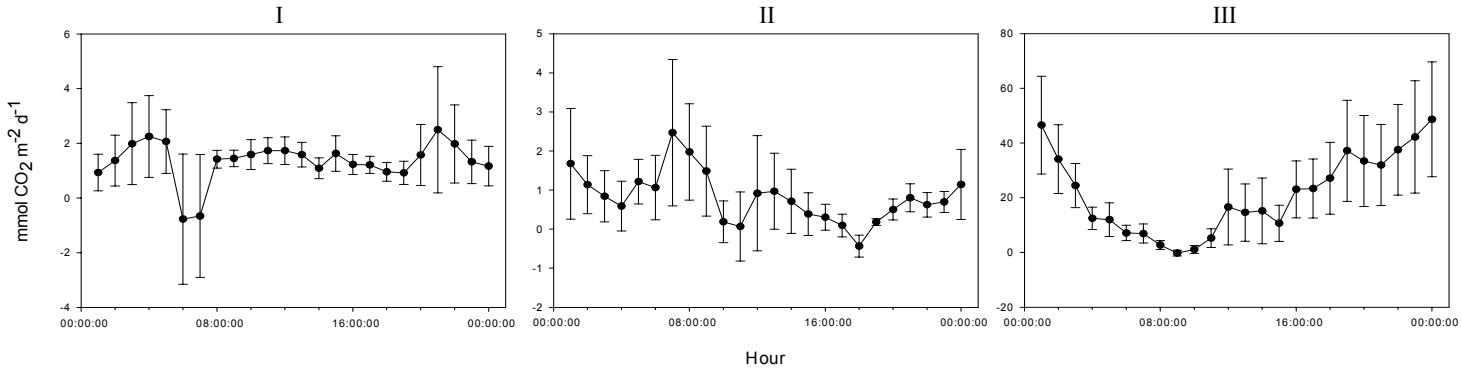


Figure 4.13a Average hourly $CO_2$ flux for three different periods over the 2005 growing season (error bars represent the standard error)

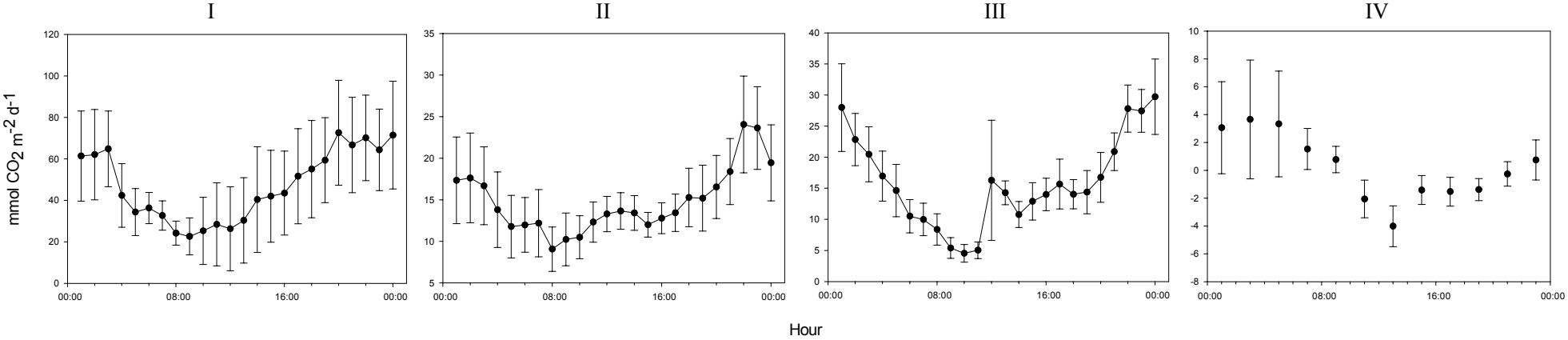


Figure 4.13b Average hourly $CO_2$ flux for three different periods over the 2006 growing season (error bars represent the standard error)

### 4.4.3 Comparison of carbon dioxide fluxes

Our data suggest that the pond acts as net source of $CO_2$ over both growing seasons. This is not uncommon as total respiration often exceeds autochthonous production in littoral zones and lakes, producing conditions in which lake waters are supersaturated with $CO_2$ with respect to the atmosphere (Cole et al.1994, Quale et al. 1995, and Schlesinger, W. 1997). Although 2005 had a warmer than normal spring it is likely that the period before the onset of photosynthesizing plants yielded optimal conditions for $CO_2$ loss. Timing of snowmelt and climatic conditions such as air temperature, soil temperature, albedo, and precipitation during the pre-leaf period (early spring) have been found to be strong determinants of the $CO_2$ source/sink potential of peatlands (Joinier et al. 1999).

It is difficult to place our results in context, given a general lack of information on carbon exchange dynamics within prairie wetland environments. Results from various studies in other wetland environments emphasize the high diversity in $CO_2$ fluxes from year to year and from one site to the next.

Sellers et al. (1995) also used the thin boundary layer technique to find the $CO_2$ flux from a wetland pond located in the Boreal Forest at the Experimental Lakes Area in Ontario, Canada, which is situated in the Canadian Shield. The average daily fluxes were similar to the fluxes found in this study (Table 4.5). Matthews et al. (2003) studied wetlands located in the Expeimental Lakes Area and the Duchemin et al. (1999) studied the area in the Taïga Region of the Canadian Shield. Both studies also used the thin boundary layer technique, to monitor wetland ecosystems, and found mean daily fluxes that were significantly less and more (respectively) than the mean daily fluxes found in this study (Table 4.5).

Table 4.5 Comparison of studies of small water bodies using the thin boundary layer equation

| | Sellers et al. | This project | Matthews et al. | Duchemin et al. |
|---|---|---|---|---|
| Site | Wetland pond at ELA | Prairie pothole wetland | Shallow flooded area at ELA | Shallow peatland |
| Year Period | Unknown (June to Aug) | August 2006 | August 2000 | September 1994 |
| Method used | TBL equation | TBL equation | TBL equation | TBL equation |
| Average daily flux (mmol/m2/d) | 18158.5 | 15344.9 | 7704.5 | 34091 |

In the spring the warming of the waters produces conditions favorable to the decomposition of organic matter. This warming process is also associated with the sinking of dead organic material. Upon sinking, the dead organic material decays and depletes of the water of oxygen, which in turn leads to lower redox potentials. An increase in nutrient availability is usually also seen at this time.

This process may account for the large $CO_2$ efflux from the pond seen in the early spring of 2006. A drop in redox potential is also seen at this time and occurs just before the large $CO_2$ efflux was measured from the pond (Figure 4.14). Because no $CO_2$ flux measurements were made prior to period I in 2006 it is likely that these high emissions were seen earlier on as well during the warming process.

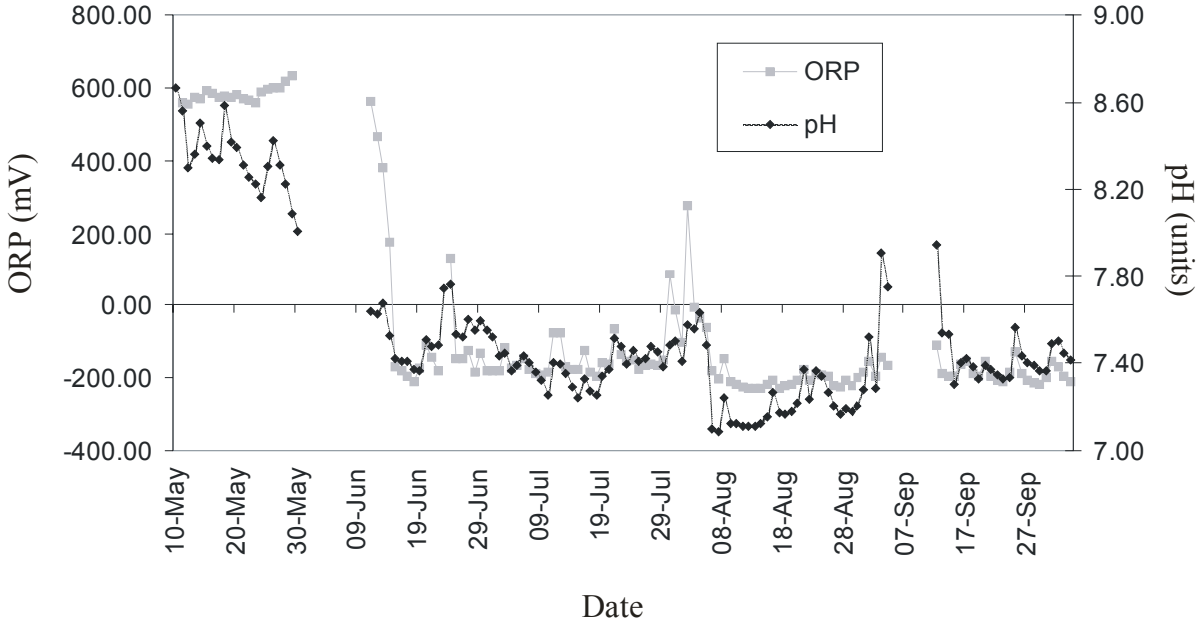


Figure 4.14 Oxidation reduction potential and pH of the pond water in 2006 (the highlighted areas correspond to the four carbon dioxide water flux measurement periods)

If in-fact, the spring warming period appears to have coincided with a large phytoplankton bloom which occurred in the spring (Figure 4.15). Therefore the large efflux of $CO_2$ from the water in the spring also appears to occur simultaneously with large phytoplankton production. Due to the short turnover rate of algae (a matter of days, see Table 2.1) and timing of peak phytoplankton production (occurring just before measurement of $CO_2$ fluxes from the water began) it is possible that the $CO_2$ measurements captured phytoplankton decomposition. It is common for algae production to be dominant in the spring and fall, while cyanobacterial productions dominates in the summer which is an attribute of warmer water and the biophysical characteristics of the cynaobacteria.

Hope et al. (1996) investigated 27 northern Wisconsin lakes to find the relationships between the partial pressures of $CO_2$ and DOC in surface waters. They concluded that the partial pressures of $CO_2$ and DOC were positively correlated. This relationship is somewhat illustrated during the 2005 growing season. Low DOC concentrations and partial pressures of $CO_2$ were maintained throughout the summer until August (when DOC concentrations increased) and September (when partial pressures of $CO_2$ increased).

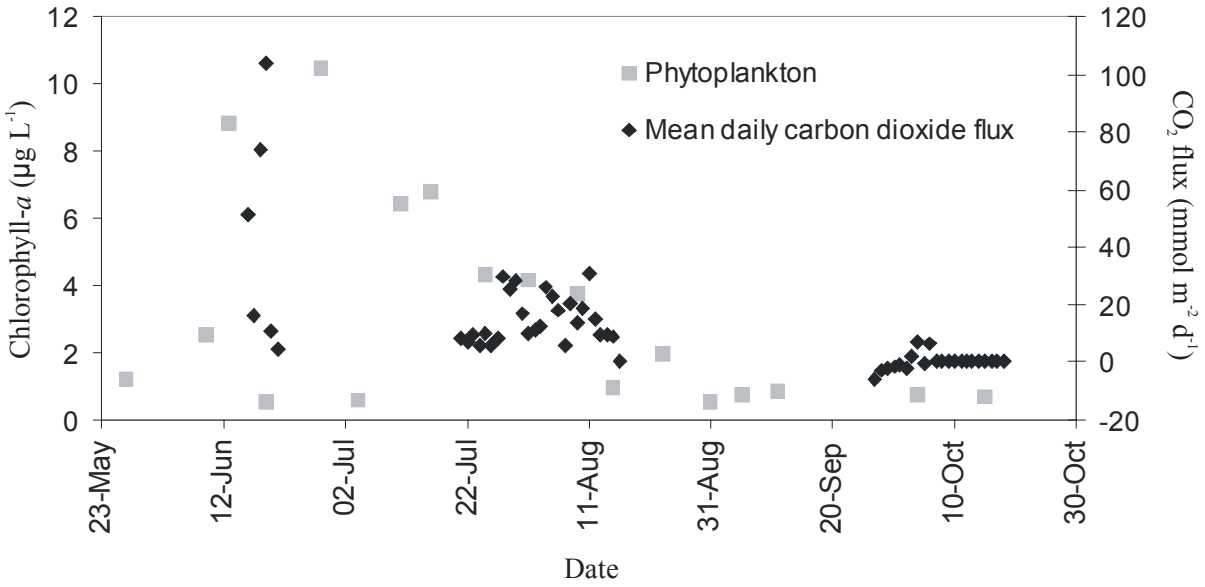


Figure 4.15 Comparison of phytoplankton production and mean daily carbon dioxide flux from the open water portion of the pond in 2006

### 4.5 Tower based $CO_2$ fluxes

The eddy correlation system measured the $CO_2$ flux from a flux footprint (described in Section 3.8) that extends beyond the confines of the wetland. Fetch to height ratios for developed surface layers range anywhere between 50:1 (for aerodynamically rough surfaces) and 300:1 (for aerodynamically smooth surfaces) (Oke, 1987). Given the height of the system (approximately 1 – 1.5 meters, considering that the water fluctuates up to ½ of a meter during the growing season), one requires an upwind fetch of approximately 100 – 150 meters, which extends far into the agricultural upland for any possible over-pond fetch direction.

The eddy correlation $CO_2$ flux was much more dynamic than the $CO_2$ fluxes measured from the pond (as seen in Figure 4.16). The seasonal pattern derived by the eddy correlation system highlights consistent fluctuations in magnitude and direction throughout the season with a notable increase in $CO_2$ uptake in late-June of 2006. This inconsistency in the data sets highlights the large influence of the cropped upland on the eddy correlation derived $CO_2$ flux.

The 2005 eddy correlation data showed no particular seasonal pattern. The flux magnitudes were different among the years and show a great deal of variability. Although both years have a similar number of periods of uptake and emissions, the 2005 flux magnitudes were much greater than in 2006. The seasonal 2005 fluxes appear to have consisted of a net efflux rather than uptake, making it a slight net source of $CO_2$. The opposite was observed in 2006. Even the dry month of July in 2006 appeared to have had no affect on the daily fluxes seen from the flux footprint. This is most likely due to the influence of the cropped upland on the flux footprint and its robustness to the different climatic variables.

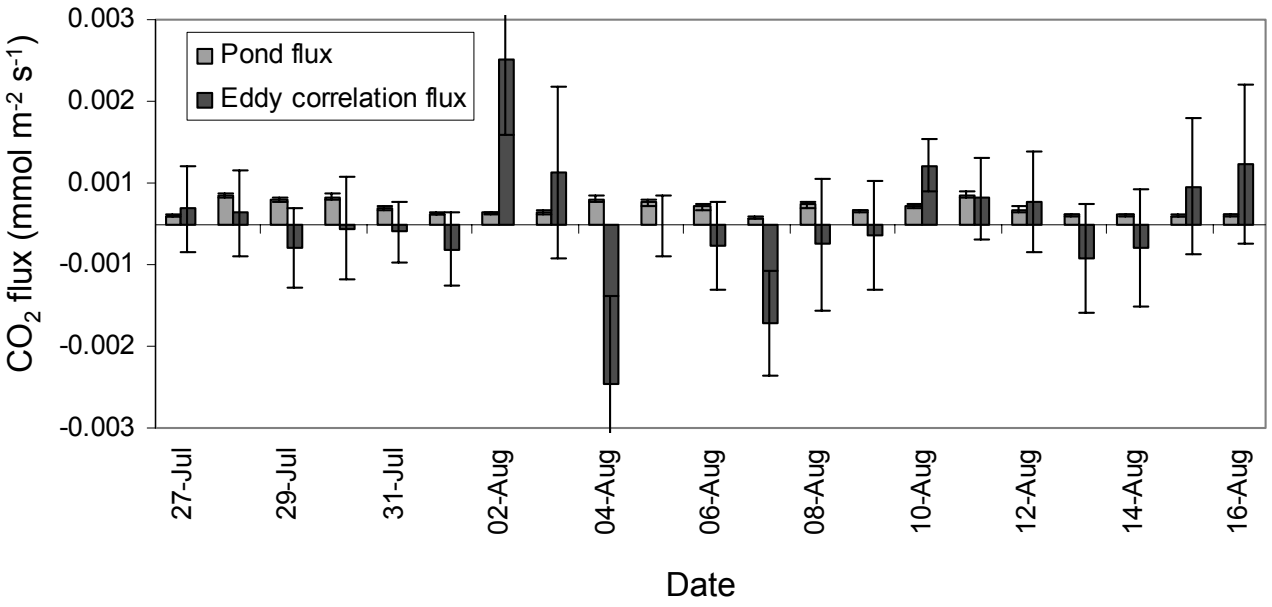


Figure 4.16 Carbon dioxide flux integrated over the flux footprint of the eddy correlation system, shown in conjunction with the pond flux in 2006

**4.6 Summary**

Production of algae (phytoplankton, epiphyton, and metaphyton) over the 2005 growing season was generally greater than in 2006. Emergent macrophyte biomass was similar for the two years but submersed macrophyte biomass was greater in 2005 relative to 2006. In 2006 there appears to be a slight drop in algal chlorophyll-*a* from each of the three

assemblages during or after the exceptionally dry conditions in July. In 2005, on the other hand, all algal assemblages tended to increase throughout the growing season.

The decrease in algal chlorophyll-*a* concentration from 2005 to 2006, may be due to a number of environmental or human induced factors. Differences may also be due to differences in sampling techniques or chlorophyll-*a* analysis. It is likely that the increase in DOC levels in the pond in 2006 limited light penetration to the point where it was limiting algal growth. The dry period in July of 2006 may have also limited nutrient availability to the pond, although nutrient data during this time suggests that the pond was hyper-eutrophic. Pathogens may be another cause of the variation in chlorophyll-*a* concentrations among years. Although often overlooked, parasitism can be just as important as other processes responsible for the decline of algal populations (Kalff, 2002). Another possible factor influencing algal production is the addition of herbicides and/or pesticides to the pond in 2006 (based on anecdotal evidence). However, the gradual decline in phytoplankton chlorophyll-*a* concentration throughout the 2006 growing season does not support this idea, as herbicide input would likely cause a large and immediate decrease algal chlorophyll-*a* concentrations. Again, it is important to understand that chlorophyll-*a* concentrations are not an accurate measurement of production and as such may not reflect the algal community production.

Dissolved organic carbon increased throughout the 2006 growing season from 30.18 to 51.69 mg/L. Dissolved organic carbon in 2005 was very low from May to July and increased significantly in August to 139.67 mg/L. Algae that produce DOC and bacteria that consume DOC in part determine the amount of DOC in the water. However, allochthonous inputs and outputs can also affect the level of DOC in wetlands. The increase in DOC levels in August of 2005 may have been due to a decrease in water level, senescence and external inputs. The higher DOC levels in 2006 were likely sustained to a certain extent over the winter. Although much less than August 2005 levels, the 2006 growing season had relatively high DOC levels in comparison to the spring of 2005.

Over the 2006 growing season the pH and DO decreased while the salinity increased. During the summer of 2005 the pH of the pond was higher than in 2006 and the water was less saline. The higher salinity in 2006 may have been due to the lower water levels. The

episodic increases in DO during the 2005 growing season were likely due to higher algal production, which in turn leads to higher decomposition rates (due to the high rate of algal turnover). The seasonal DO trend did not correlate with the $CO_2$ fluxes for either year, as would be expected. This lack of correlation may be missed due to the lack of $CO_2$ flux data and/or inaccuracies in the DO data.

Fairly neutral $CO_2$ fluxes from the pond (slight emissions or uptake) occurred during the 2005 growing season. At the end of the season, however, high $CO_2$ emissions were followed by a slight uptake of $CO_2$. In 2006 large $CO_2$ emissions at the beginning of the season were followed by moderate emissions during the growing season, and a small uptake at the end of the season. There was a strong diurnal pattern for all four periods in 2006, which consisted of lower $CO_2$ emissions during the day and higher $CO_2$ emissions at night. In 2005 a diurnal $CO_2$ pattern was only present for the third period.

The net efflux that occurred over the 2005 and 2006 growing seasons is concurrent with other littoral zones, which have been found to evade $CO_2$. In such cases, waters can become saturated with $CO_2$ when respiration and decomposition exceed productivity. The warming of the pond water in the spring (period I) of 2006 may be the reason for the high $CO_2$ effluxes during this time. In 2005 DOC and $CO_2$ fluxes followed a similar seasonal pattern, low throughout the growing season and increasing in the fall. No direct relationship was found between algal chlorophyll-*a* and $CO_2$ fluxes. This is likely because algal chlorophyll-*a* can be a poor indicator of algal productivity which may have correlated with the $CO_2$ fluxes.

The average daily $CO_2$ flux measured by the eddy correlation system for 2005 and 2006 oscillated between a source and sink, and did not correspond with precipitation events or temperature. Although the eddy correlation effluxes and uptake were of a much greater magnitude in 2005 than 2006, the system was not directly correlated with the $CO_2$ fluxes from the pond. The vast difference between the fluxes from the eddy correlation system and the open water emphasizes the impact of the cropped upland on the flux footprint. It is logical to conclude that this system is inappropriate for measuring small-scale wetlands, such as prairie pothole wetlands, due to the nature of the instrument.

# 5.0 RESULTS AND DISCUSSION: RIPARIAN ZONE

## 5.1 Basic Hydrology, soil temperature and soil moisture

Two wells were monitored during the 2006 growing season (Section 3.7) to record the depth of the water table at the riparian-wetland fringe (well 1) and at the riparian-crop fringe (well 2). The well located at the riparian-wetland fringe experienced a dramatic increase in water table level in late-June (Figure 5.2), which corresponded with a large rain event (Figure 5.5). The water table level at the riparian-crop fringe was more stable and exhibited an overall gradual decrease in the water table level until mid-August when it decreased dramatically. This may be due to transpiration from the crop and wetland fringe, which was drawing water up-slope from the wetland. Both wells were dry by mid-August.

Soil temperature was relatively similar for all points along the large chamber transect (Figure 5.1 and 5.3). From July 12$^{th}$ to August 22$^{nd}$ RB was a couple of degrees cooler than the other points along the transect. This is most likely because this point was shaded by the cattails and more moist because of its proximity to the pond (Figure 5.4). On June 7$^{th}$ soil temperature at R1 and RA were particularly high and may be erroneous. Excluding these high values, soil temperatures for all points along the transect peaked between July 26$^{th}$ and August 11$^{th}$, and slowly decreased thereafter.

Soil moisture for R1 and R3 decreased dramatically from 100% on April 27$^{th}$ to 40.6% and 56.7% (respectively) on May 30$^{th}$ (Figure 5.4). RA and RB stayed saturated until June 7$^{th}$ and August 3$^{rd}$ (respectively), much longer than was observed at the other landscape positions. Soil conditions at R3 and RA were temporarily re-saturated around mid-June, and dried up again by late-June. RA was re-saturated in early-July and dried up by late-July. RA then continued to dry up until August 11$^{th}$ (producing dryer soil conditions than the rest of the transect points), at which time it was once again re-wetted and dried up at the end of the season. RA had the most variable soil moisture content and seemed very vulnerable to rain and drying conditions. The least variable site appeared to be R2, which had a relatively constant soil moisture content through out the growing season. This difference in seasonal soil moisture content is likely due to vegetation, soil type and landscape position (more information on vegetation types is available in Section 3.6).

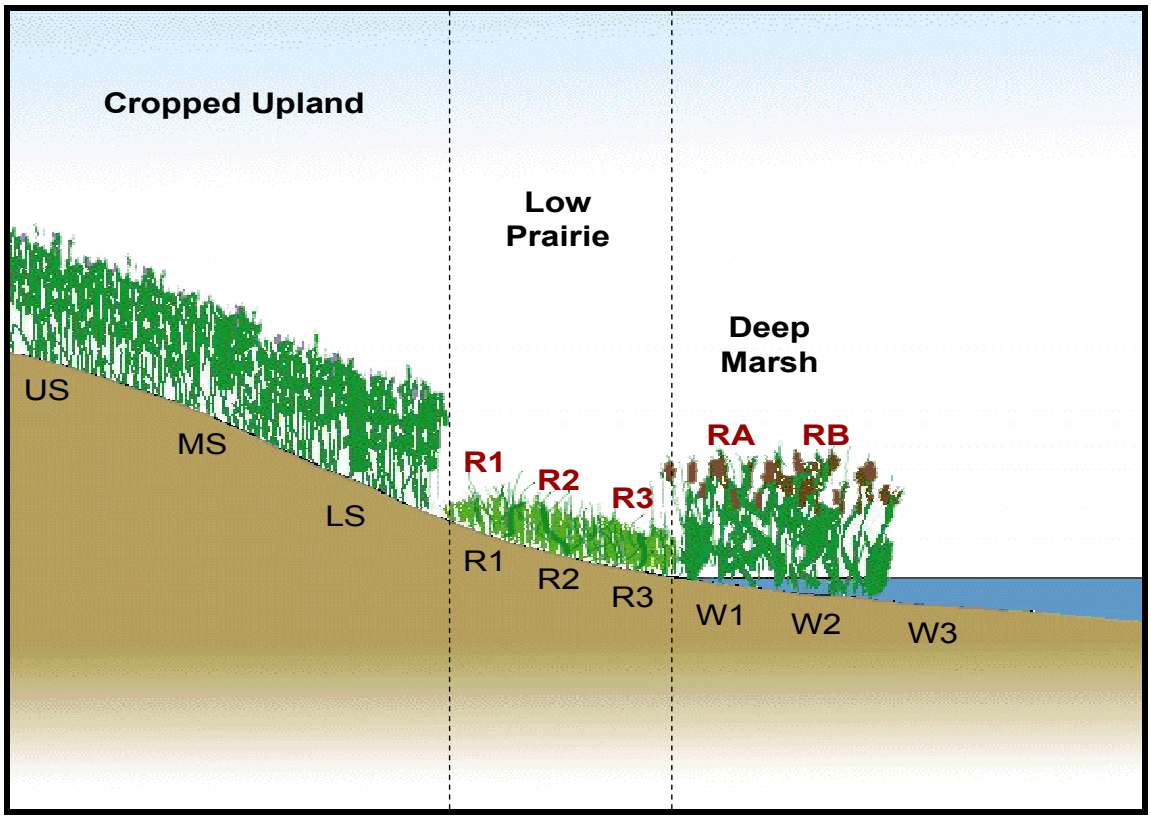

Figure 5.1 Wetland schematic showing the small soil respiration chamber transect (in regular test) and large canopy scale transect (in bolded text)

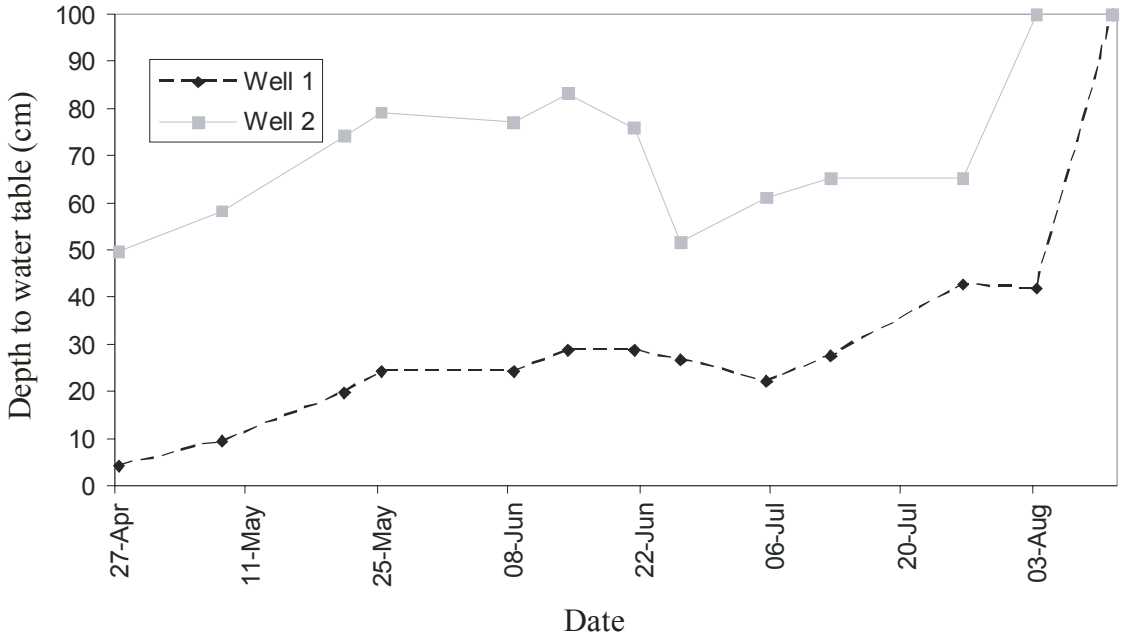

Figure 5.2 Depth to water table as measured in two wells. Well 1 is located at the cattail-sedge fringe and well 2 is located at the grass-crop fringe (2006)

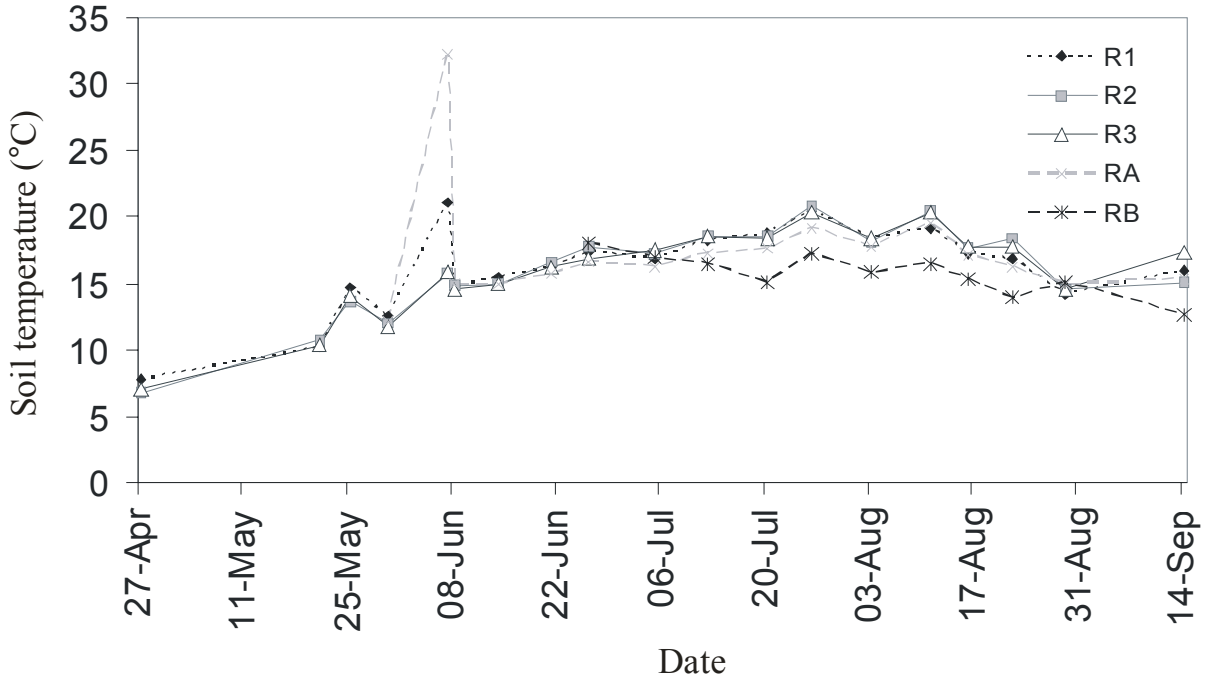


Figure 5.3 Soil temperature for the corresponding chamber positions (2006)

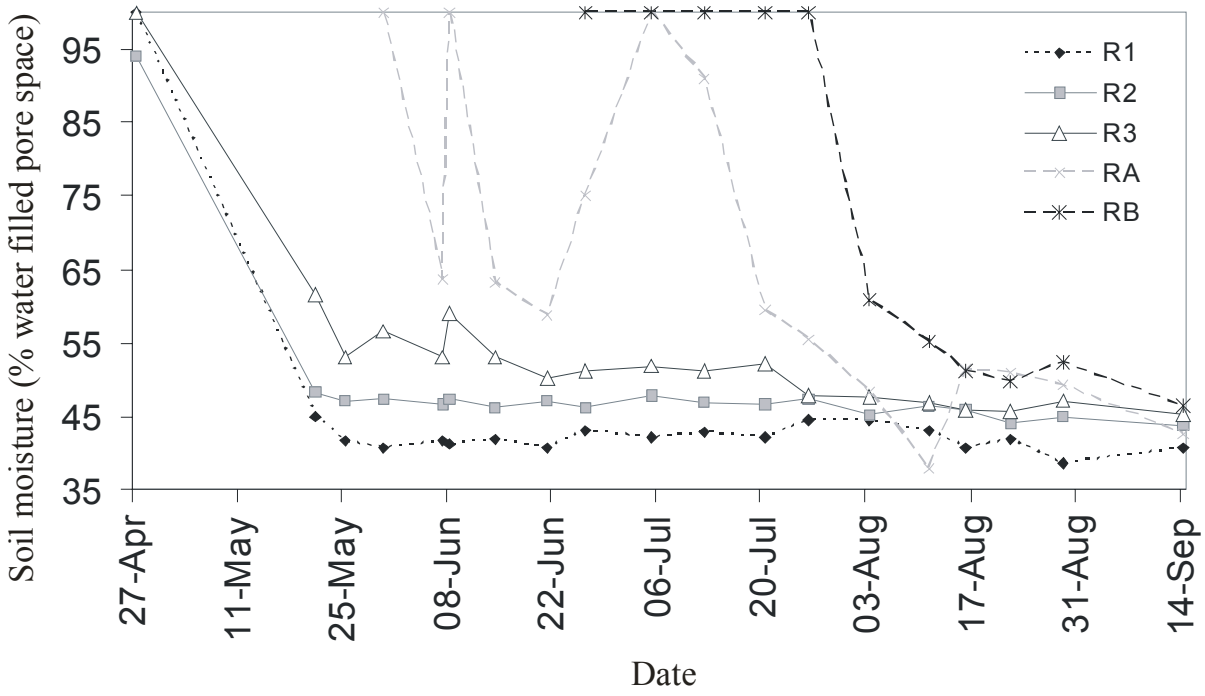


Figure 5.4 Volumetric soil moisture content (%) for the corresponding chamber positions (2006)

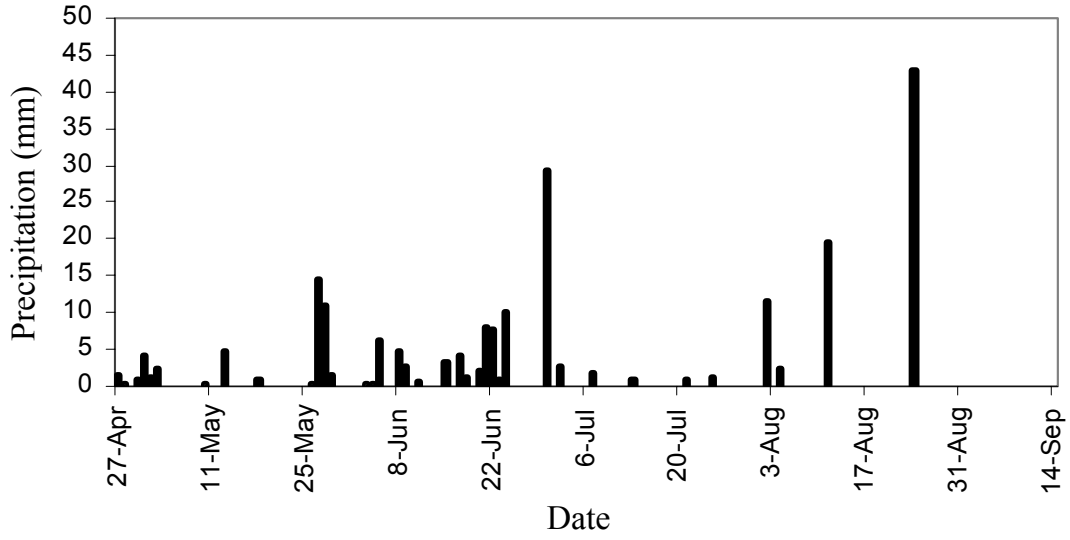


Figure 5.5 Total daily precipitation over the 2006 growing season

**5.2 Riparian Vegetation**

In this section three landscape zones are examined they include the Cropped Upland, Low Prairie and Deep Marsh zone. The Low Prairie zone often has a more porous soil, which allows percolation, to deeper sediments, to occur rapidly (Stewart and Kantrud, 1971). As a result, surface water in the Low Prairie zone is present for only a short period in the early spring. This zone is influenced by the dynamic fluctuation in water levels that are characteristic of prairie pothole wetlands. These wet-dry cycles are driven by spring runoff, summer precipitation and evapotranspiration. This affects the timing of growth and type of vegetation (producing large variations from year to year). Vegetation in this zone consists of fine-textured grasses, rushes, and sedges. This vegetation is of relatively low stature in comparison to the Deep Marsh zone. R3 contained one stunted cattail and no foxtail barley, which was present in both R2 and R1.

The Deep Marsh zone is much different than the Low Prairie zone in terms of productivity, efficiency, species diversity, meteorological requirements and basic plant function. The hydrology of this zone is highly variable with the growing season and between years. This greatly affects the ecosystem functioning of this zone. The vegetation in this zone

consists largely of emergent macrophytes, because of the degree of soil saturation and/or water level. The dominant vegetation in the Deep Marsh zone was *Typha* spp.

The third zone is the Cropped Upland which was managed by the Zero-Tillage Research Association farm. The field in which the small chamber transect was located was seeded in Canola in 2005 and Alfalfa in 2006. These uplands have superior drainage than the depressions and contain less organic matter.

In 2006 emergent macrophyte biomass appeared to decrease upland in the Low Prairie zone of the large chamber transect (Figure 5.6). In the Low Prairie zone, R3 had significantly less biomass ($p=0.05$) than R1 and R2. In 2005 biomass of three points in the Low Prairie zone was not statistically different ($p=0.05$). In 2006 the two points in the Deep Marsh zone were comparable in terms of their biomass (were not statistically different at $p=0.05$). In fact they had a similar number of cattails of similar size. In the Deep Marsh zone the only vegetation type present along the biomass transect at points RA and RB was *Typha* spp. and as such was the only vegetation type harvested and measured for biomass. Production of *Typha* spp. stands, in the north central U.S.A., have been measured in multiple studies and summarized by Dubbe et al. (1988) as 4.3 - 14.8 dry Mg $ha^{-}1$ (0.43 – 1.48 kg $m^{-2}$) for above ground biomass and 4.9 - 9.2 dry Mg/ha (0.49 – 0.92 kg $m^{-2}$) for below ground biomass.

The type of vegetation and leaf area index strongly affects the $CO_2$ fluxes from the riparian zone. In turn the functioning of the vegetation can be related back to environmental conditions. Sims and Bradford (2001) related changes in inter annual tall grass prairie $CO_2$ fluxes to the leaf area index (LAI) as well as environmental conditions; especially droughts, cloudiness, and temperature stress.

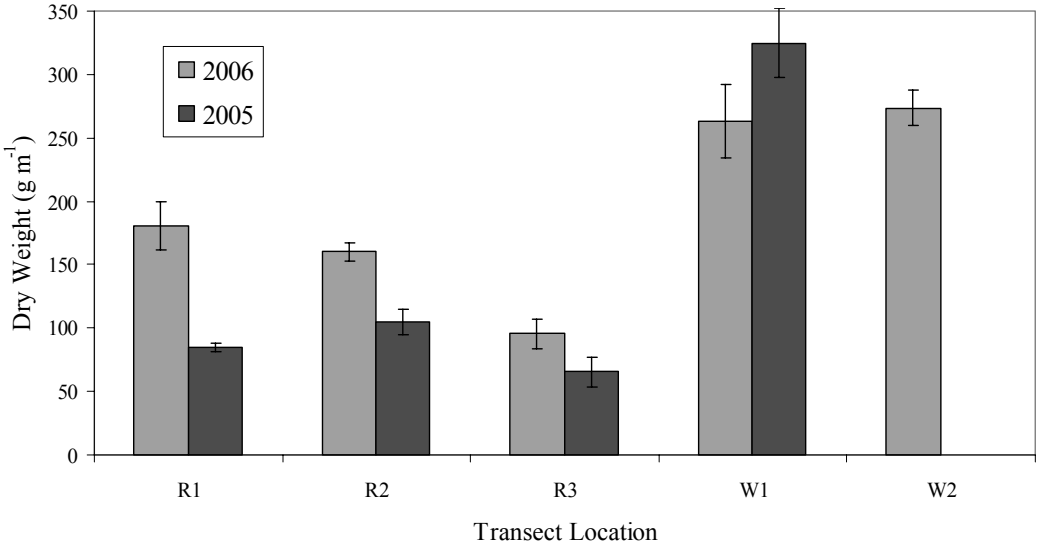


Figure 5.6 Biomass by weight for 2005 and 2006. The error bars denote the standard error

### 5.3 Seasonal $CO_2$ fluxes: Small chambers

In 2005 and 2006 soil respiration in the Low Prairie zone was measured using small opaque chambers. Measurements using these small respiration chambers, were also taken in the Deep Marsh and Open Water zone (herein collectively referred to as the Deep Marsh zone) and Cropped Upland (details on transect location and landscape position in Chapter 3). In the Deep Marsh zone, small floating chambers were used when water was present (details on the chamber type and position appear in Section 3.4). Although there was no significant difference between the seasonal $CO_2$ fluxes from the Low Prairie, Deep Marsh or Cropped Upland in 2006, each were significantly different from one another in 2005 ($p=0.05$). In 2005 the $CO_2$ fluxes from the three points within each of the three landscape zones (Low Prairie, Cropped Upland and Deep Marsh) behaved very similarly over the season. There was an increase in the $CO_2$ fluxes from the three landscape zones with increasing elevation and distance from the pond proper.

### 5.3.1 Low Prairie

The seasonal pattern exhibited over the 2005 growing season in the Low Prairie transect (Figure 5.7) is consistent with other studies (Mielnick and Dugas, 2000). The 2006 seasonal patterns appear to be less consistent and more erratic. The 2005 seasonal pattern for the Low Prairie transect starts with low $CO_2$ emissions in April then increases consistently until July, at which time the effluxes slowly fall until mid-November, where they remain close to zero – typical of a native prairie surface (Mielnick and Dugas, 2000). The system switches from a source to a sink between late-September and early-November. A striking difference between years is the slow 2006 springtime rise in $CO_2$ emission. Although there is no statistical difference between R1, R2 and R3, R3 appears to deviate from the seasonal trend exhibited by R1 and R2 from mid-June to early-August.

The 2006 winter fluxes (measured in February and March) consisted of very low emissions or a slight uptake (Figure 5.8). This is concurrent with findings by Sims and Bradford (2001) who found that late winter and early spring carbon dioxide fluxes from native grasslands in the southern prairies were near neutral. In 2006 the $CO_2$ fluxes from the three points along the Low Prairie transect began to increase in the middle of April, but peaked at various times throughout the growing season. Despite the variation in peak $CO_2$ flux emission occurrence, all three points had a similar seasonal increasing trend. The $CO_2$ flux slowly increased from February to mid-May (not shown), and decreased sharply thereafter (at this point there was a flux direction reversal for R1 and R3). The $CO_2$ fluxes then increased (back to mid May levels) and stayed fairly constant from July to August. Although the points in the Low Prairie zone were not statistically different from one another, R3 appeared to have smaller fluxes in late-April and early-May and larger fluxes in late-July and early-August, where as R1 had larger fluxes earlier in the season and smaller fluxes later in the season. The seasonal $CO_2$ fluxes from R2 and R1 were very similar, except at the end of the season and in early-May.

Fluxes from this zone ranged from 119 to -2 mmol $CO_2$ $m^{-2}$ $d^{-1}$ in 2005 and from 82 to -31 mmol $CO_2$ $m^{-2}$ $d^{-1}$ in 2006. Although negative fluxes are not generally expected when measuring soil respiration, there are two reasonable explanations for this. The first is

photosynthesis by vegetation, that was missed during the clipping process (part of the sampling procedure). The second being error resulting from the flux calculations.

### 5.3.2 Deep Marsh

In 2005 the Deep Marsh zone exhibited a seasonal curve with maximum emissions occurring in mid summer (Figure 5.7). There was a gradual decrease in $CO_2$ flux emissions from mid July to mid-November, with the exception of a mid September peak in the two most inland points. In 2006, however, peak $CO_2$ emissions occurred in mid-May at point W1 and early-July at W2 and W3 (Figure 5.8). Fluxes from this zone over the growing season ranged from 50 to -2 mmol $CO_2$ $m^{-2}$ $d^{-1}$ in 2005 and 50 to -2 mmol $CO_2$ $m^{-2}$ $d^{-1}$ in 2006. The exceptionally high early-July efflux from W3 may be erroneous. After the mid-summer peak in July, the most inland point (W1) continued to increase while the other two decreased. This may be due to the lack of summer precipitation, which created inadequate conditions for soil respiration. There was no significant difference in $CO_2$ fluxes from the three landscape positions within the Deep Marsh zone over the 2005 and 2006 growing seasons ($p=0.05$).

### 5.3.3 Cropped Upland

Over the growing season, fluxes from this zone ranged from 137 to 13 mmol $CO_2$ $m^{-2}$ $d^{-1}$ in 2005 and 86 to -58 mmol $CO_2$ $m^{-2}$ $d^{-1}$ in 2006. In 2005, the seasonal $CO_2$ emission trend in the Cropped Uplands was similar to that in the Low Prairie and Deep Marsh (Figure 5.7). Differences, however, are present at the beginning of the sample period in early-April when emissions were much higher. By early-May the $CO_2$ emissions from this area start the assent to maximum summer emissions, which occur in late-July, and gradually decreased thereafter. In 2006 the $CO_2$ fluxes from the Cropped Upland were fairly low and oscillated between emissions and uptake from mid-February to late-April (data not shown). In early-May the upper and mid slope began to sequester $CO_2$ while the lower slope increased as a source of $CO_2$ (Figure 5.8). In early-June the upper and mid slope switched from a sink to a source, and all three point in the Cropped Upland increased to a mid-summer peak in mid-July (with the exception of a small decrease in emissions in late June). $CO_2$ fluxes decreased

dramatically between the mid-summer peak and the next sample date (mid-September). There was no significant difference in $CO_2$ fluxes from the three landscape positions within the Cropped Upland over the 2005 and 2006 growing seasons ($p=0.05$).

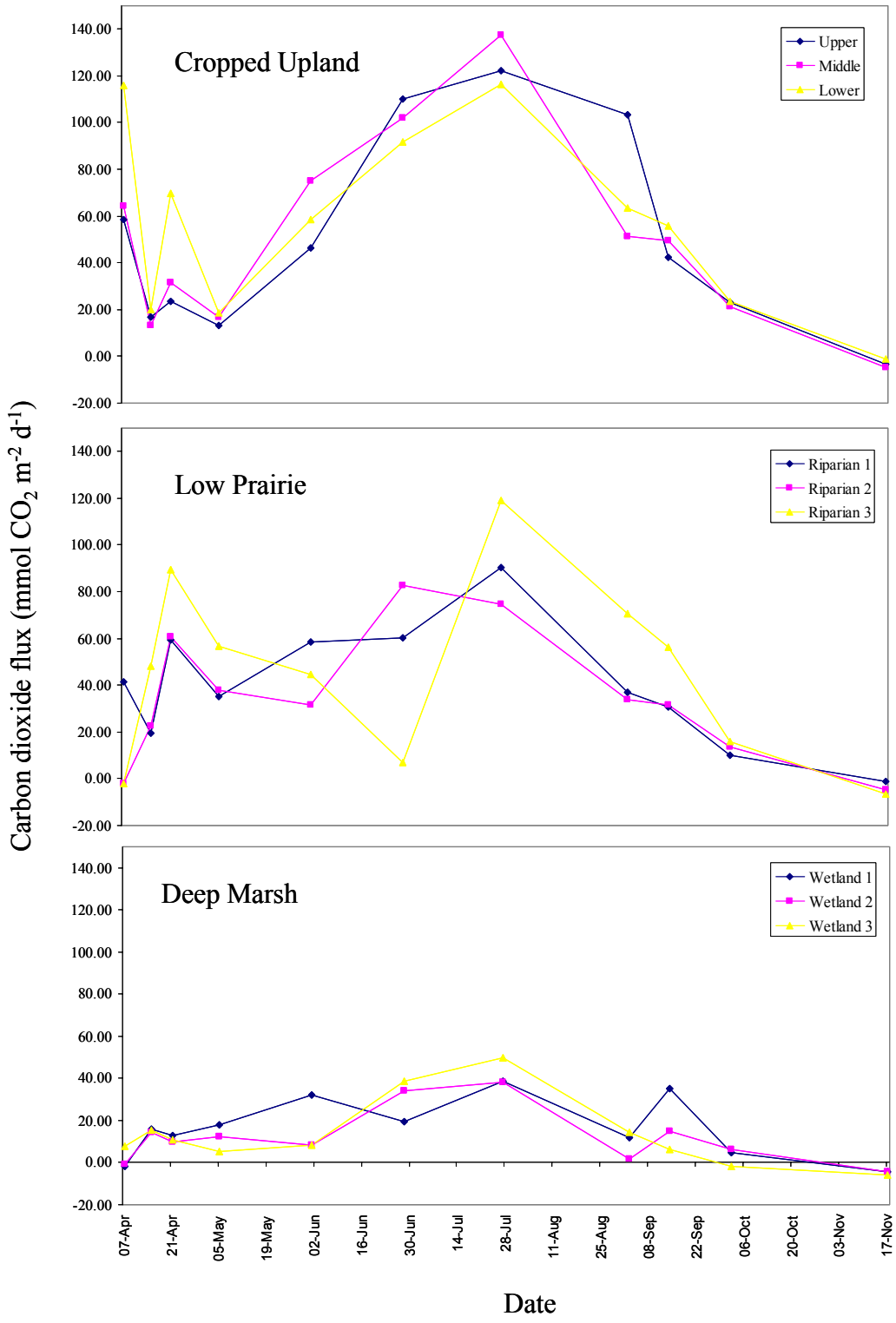


Figure 5.7 $CO_2$ fluxes from the Cropped Upland, Low Prairie and Deep Marsh of the Deep Crop Wetland for 2005

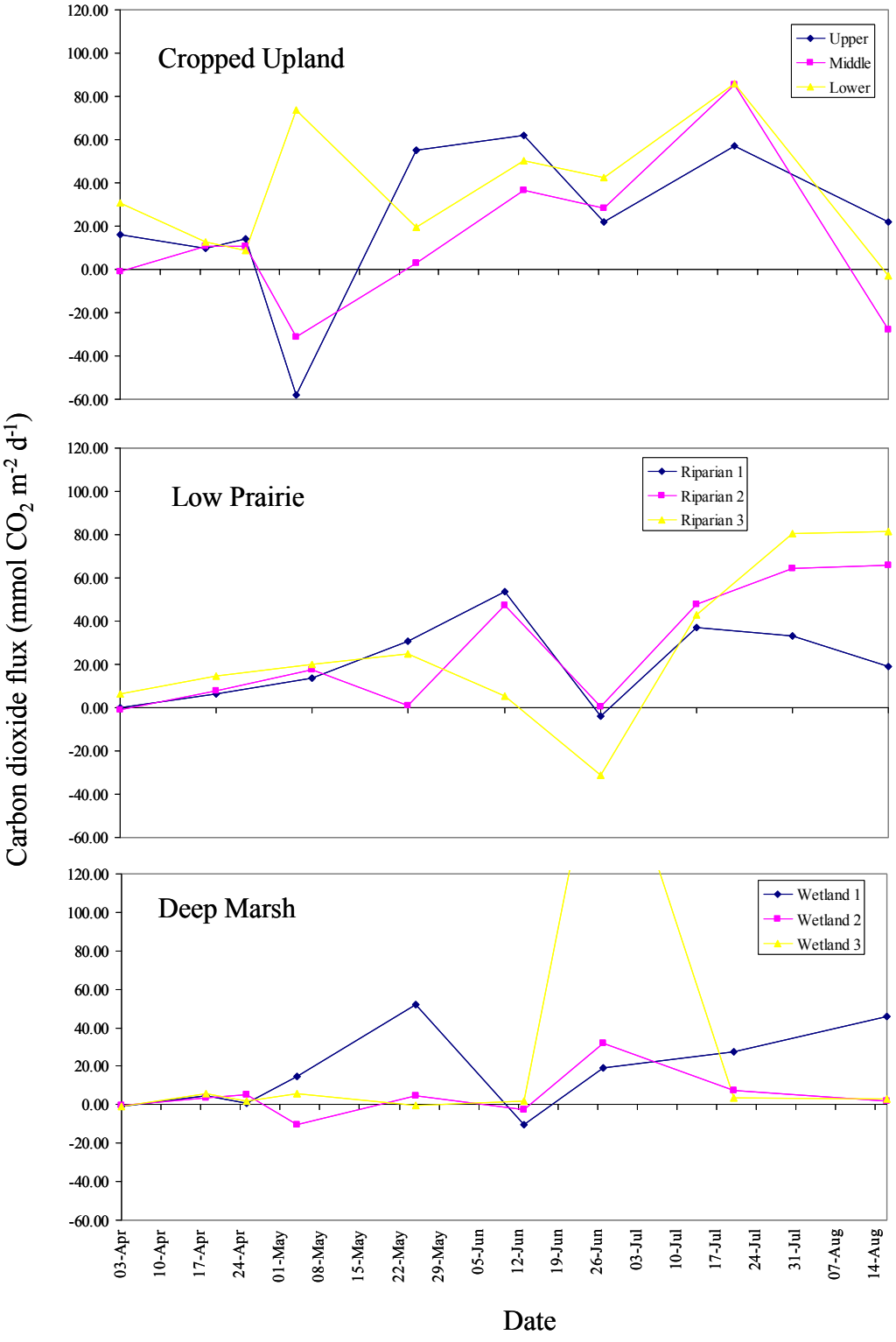


Figure 5.8 $CO_2$ fluxes from the Cropped Upland, Low Prairie and Deep Marsh of the Deep Crop Wetland for 2006

### 5.4 Seasonal $CO_2$ fluxes: Large chambers

The net $CO_2$ flux or net ecosystem exchange (NEE) of the Low Prairie zone was measured throughout the 2006 growing season (from April to September) on a weekly basis (with the exception of 2 weeks in May) using a large plexi-glass chamber (details on this chamber can be found in Section 3.4). The seasonal range of NEE magnitudes was similar for the three landscape positions in the Low Prairie area, throughout the growing season (Figure 5.9). NEE ranged from 280 to -1520 mmol $CO_2$ $m^{-2}$ $d^{-1}$ in this zone. Over the course of the growing season all points along the transect had a net $CO_2$ uptake, when considering only the photosynthetically active periods of the day. The magnitude of uptake decreased for two consecutive sampling periods (late July and early-August), and in one case the direction of the flux switched from a sink to a source. This decrease in uptake followed the summer drying conditions experienced during the month of July. Sims and Bradford (2001) and Meyers (2001) also found that integrated canopy $CO_2$ fluxes from naturally grassed areas were particularly sensitive to low soil moisture.

The seasonal NEE pattern of all three landscape positions, in the Low Prairie zone, highlights the variability in plant uptake from one point along the transect to another (Figure 5.8). There was, however, no significant difference between the three locations in the Low Prairie zone ($p=0.05$). Because of the steep vegetation gradient along the transect, all three points in the riparian zone contained a unique variety of vegetation types (more information on vegetation types along the transect available in Section 3.6). This difference in $CO_2$ fluxes from the within the Low Prairie zone was not seen in the respiration fluxes (Figure 5.10). Although all three points exhibited a unique seasonal pattern, they all show an increase in respiration on June 16$^{th}$ (Figure 5.9), at which point there was also an increase in soil temperature (Figure 5.3).

The two points in the Deep Marsh section behaved similarly in terms of NEE and respiration fluxes throughout the 2006 season (Figure 5.9 and 5.10). Seasonal fluxes ranged from 696 to -2754 mmol $CO_2$ $m^{-2}$ $d^{-1}$ in this zone. Uptake at these two points exceeded the uptake from the Low Prairie zone. At the end of the season, however, RA remained a small $CO_2$ sink while RB switched to a source.

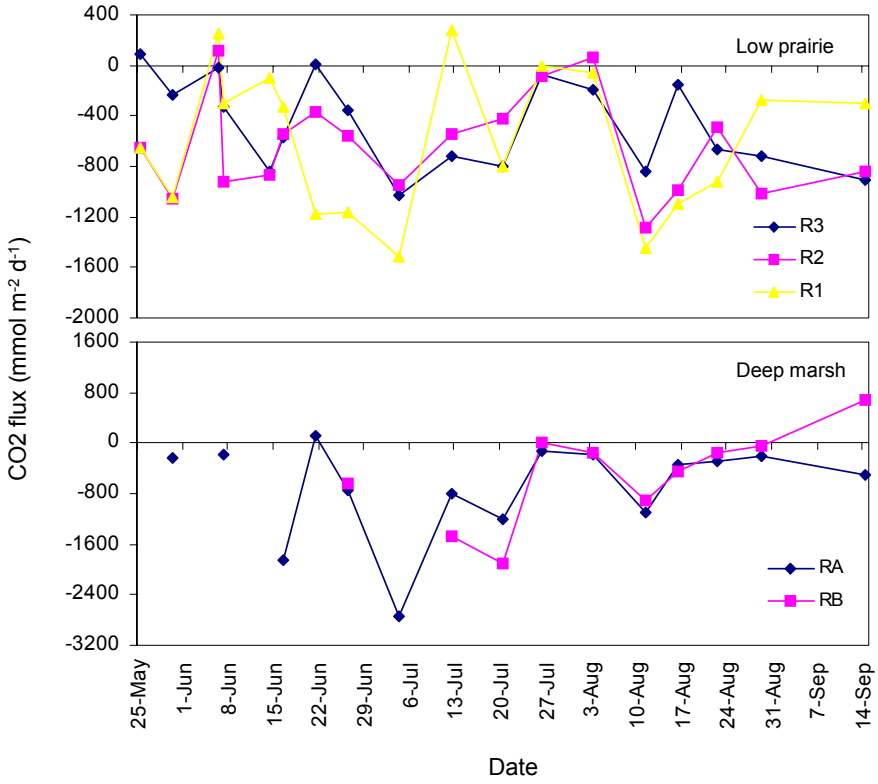


Figure 5.9 Net ecosystem exchange for the Low Prairie and Deep Marsh section of the transect (2006)

The opaque chambers, used for this study, measured soil, root and plant respiration. The magnitude of the respiration fluxes were fairly similar throughout the season for the three chambers in the Low Prairie area, with the exception of one sample period in the middle of June when respiration rates rose dramatically (Figure 5.10). This increase was seen at all points along the transect and may be incorrect, as this sampling technique is subject to errors. Fluxes from the Low Prairie zone ranged from 4916 to -1068 mmol $CO_2$ $m^{-2}$ $d^{-1}$. Fluxes from the Deep marsh ranged from 1321 to -130 mmol $CO_2$ $m^{-2}$ $d^{-1}$. Only one point in the Deep Marsh section was being measured at this time and although respiration rates were slightly higher than during the rest of the season, these emissions were not as low as those in the Low Prairie zone.

There was a decrease in $CO_2$ uptake on July 20$^{th}$ and July 26$^{th}$ 2006, there is a decrease in $CO_2$ uptake by both the Low Prairie and Deep Marsh plants. The reduction in $CO_2$ uptake occurs during the warm and dry period in July. During this time, respiration rates

did not increase (Figure 5.10), which would suggest that the neutral NEE occurred because of a decrease in plant photosynthesis.

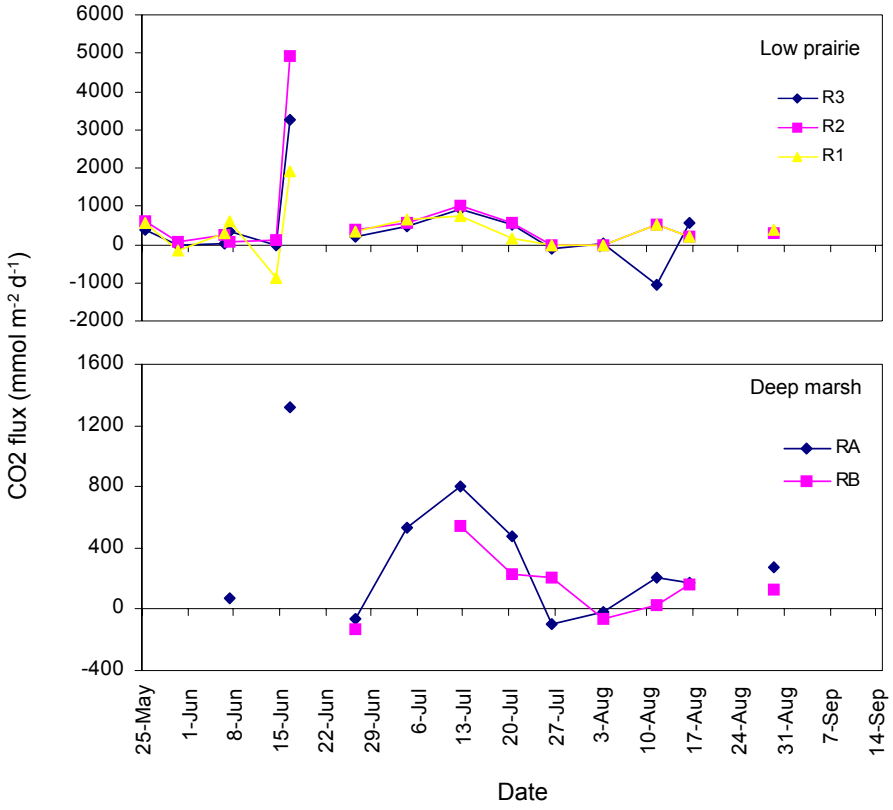


Figure 5.10 Respiration flux for the Low Prairie and Deep Marsh section of the transect (2006)

## 5.5 Diurnal $CO_2$ fluxes: Large chambers

### 5.5.1 Net Ecosystem Exchange

Diurnal NEE was measured four times throughout the season (once in April, June, July and August). The diurnal flux patterns for the Low Prairie and Deep Marsh zone follow a seasonal trend that entails a net uptake during the day and release at night (Figure 5.11). $CO_2$ uptake occurs during the photosynthetically active portion of the day when the plants (in the riparian zone) are actively assimilating carbon; the opposite is true for the night, during which time the plants are respiring. The diurnal pattern of the Low Prairie segment is similar for June, July and August. April, however, is different in that it stays relatively neutral

throughout the day. These neutral (slightly positive) April fluxes are likely due to the fact that the bulk of the vegetation growth has not yet begun. Instead the fluxes likely represent emissions from soil respiration and/or plant litter decomposition (Kuehn et al. 2004). The moist soil conditions in the early spring did not last long (unlike the warm temperatures) and the soil dried up quickly, resulting in warm arid conditions which likely promoted a $CO_2$ efflux (Griffis et al., 2000; Carroll and Crill 1997). Although August had the highest daytime $CO_2$ assimilation, it also had the highest nighttime $CO_2$ effluxes.

For the June, July and August samplings, the Low Prairie segment acted as a $CO_2$ sink (or a very small source, as was the case for the August sampling) between 700h and 1500h. Between 1500h and 1900h the system switched from a sink to a source and continued to act as a source until 300h. It is between 300h and 700h that the system switched back to a sink. This pattern was also seen during the months of June and July along the Deep Marsh transect. The August pattern differed from April, June and July in that the sink to source transition occurred earlier (between 1100h and 1500h) and switched from a source to a sink earlier (between 2300h and 300h). The nighttime $CO_2$ emissions from the Deep Marsh segment are larger than for the Low Prairie segment in June, but lesser in August. This may reflect the phenological development of the aquatic plants versus the terrestrial sedge/grass plants. This nighttime flux is often more closely linked to soil temperature. The conversion of the ecosystem from a source to a sink occurs earlier in August which is counter intuitive to what would be expected with shorter daylight hours, and may be a function of the particular climatic conditions on the day of sampling, and may be due to the particular climatic and biotic factors at play that particular day.

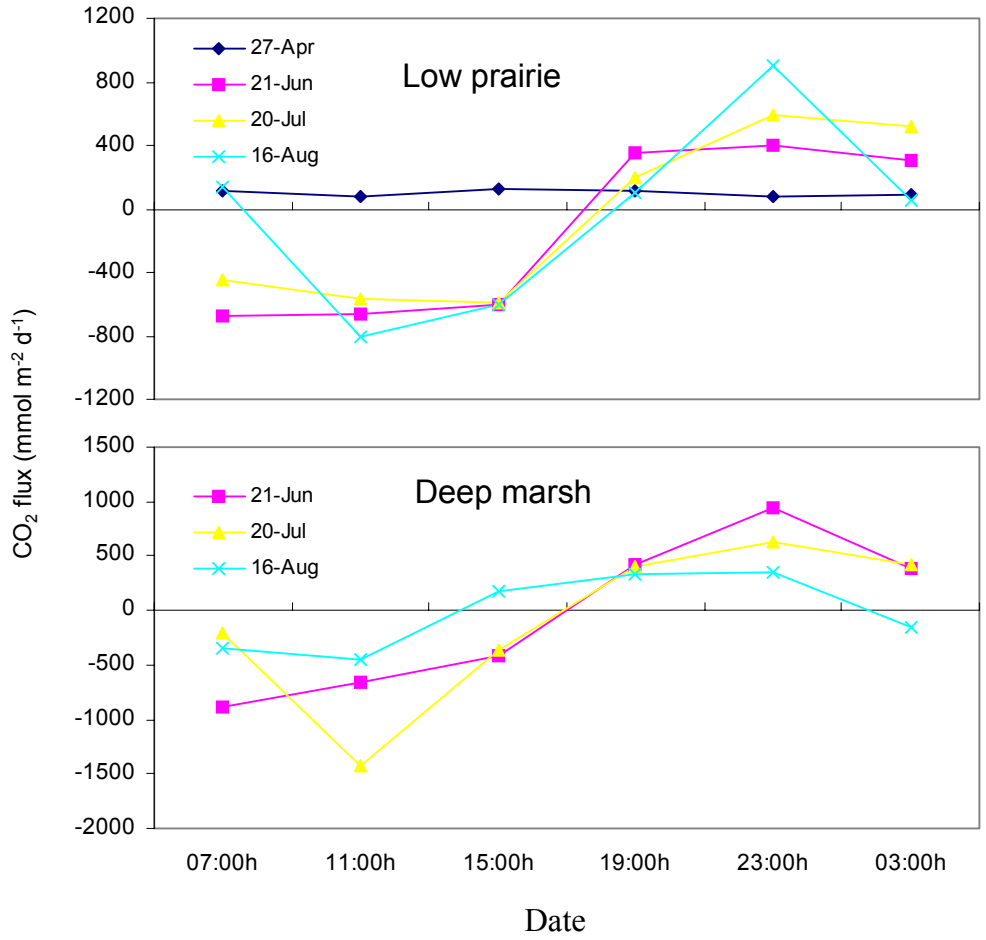


Figure 5.11 Diurnal net carbon dioxide flux for the Low Prairie (R1, R2 and R3) and Deep Marsh (RA and RB) segment (2006)

Bonneville et al. (2007) measured the diurnal $CO_2$ fluxes from a cattail marsh and found similar diurnal patterns, to this study, for both the spring and summer fluxes (Table 5.1). Although they did not have a diurnal summary for April, the average diurnal trend for May was similar to the trend for April in this study. Both were very neutral and slightly positive, showing very little pronounced diurnal pattern. This is to be expected as the vegetation has likely not started grow and photosynthesize by this time. The average daytime fluxes from the Low Prairie zone in this study for June, July and August are –648.6, -539.0, -422.2 mmol $CO_2$ $m^{-2}$ $d^{-1}$ respectively. In comparison Bonneville et al. (2007) found the mean daytime $CO_2$ fluxes for June, July and August to be –155.5, -777.6 and –881.2 mmol $CO_2$ $m^{-2}$ $d^{-1}$ respectively (Table 5.1). The higher June $CO_2$ influx that was seen in this study was likely due to the warm and wet spring conditions which prompted early growth.

The nighttime emissions from this study ranged from 350.5 – 436.1 mmol $CO_2$ $m^{-2}$ $d^{-1}$, with the largest fluxes occurring in July. In comparison, Bonneville et al., (2007) found smaller nighttime fluxes from June to August which ranged from 207.3 – 224.6 mmol $CO_2$ $m^{-2}$ $d^{-1}$. There are many factors which can influence $CO_2$ fluxes from wetlands. Differences in climatic conditions such as the onset of spring can stimulated or delay early plant development. Other factors include to vegetation type, hydrology the amount and quality of organic matter available to facilitate the respiratory processes.

Table 5.1 Comparison of average daytime and nighttime fluxes

| **Study** | **Sims and Bradford (2001)** Grassland | | **This study** Low Prairie | | **Bonneville et al. (2008)** Low Prairie | |
|---|---|---|---|---|---|---|
| Day/Night | Daytime | Nighttime | Daytime | Nighttime | Daytime | Nighttime |
| **June - July** | -1335.3 | 392.8 | -609.0 | 451.3 | 155.5 – (-838.08) | 216 - 224.6 |

5.5.2 Respiration

Respiration from both transect segments were measured to assess diurnal emission patterns. In this case, nighttime respiration fluxes are the same as the NEE nighttime fluxes. $CO_2$ emissions during the day were typically not as great as the emissions during the night (Figure 5.12). In the Deep Marsh segment there was a decrease in $CO_2$ emissions at 2300h. The $CO_2$ flux emissions during the day were slightly lower for the Deep Marsh segment, and switched to a sink in June at 1100h. The August sampling of the Low Prairie zone shows a variable flux not consistent with any other diurnal patterns. During this time the diurnal pattern of the Deep Marsh zone was also more variable than the other months but still has a recognizable pattern.

The chambers not only measure canopy photosynthesis and respiration, but also $CO_2$ effluxes from plant litter, which is stimulated by microbial activity. Kuehn et al. (2004) found that the portion of the diurnal wetland flux (represented by microbial induced $CO_2$ evolution from P. *Australis* shoots) is mediated by temperature changes (as well as changes in relative humidity and litter water potential). They found that rates of $CO_2$ emissions were highest in the morning and decreased rapidly during the drying periods. In this study $CO_2$

emissions did not appear to be highest in the morning, but rather late at night. This may be because unlike Kuehn et al. (2004) respiration may have been dominated by plant and soil respiration, not microbial litter decomposition. It may also be due to a difference between sites, as a huge degree of variability has been found to exist between wetlands.

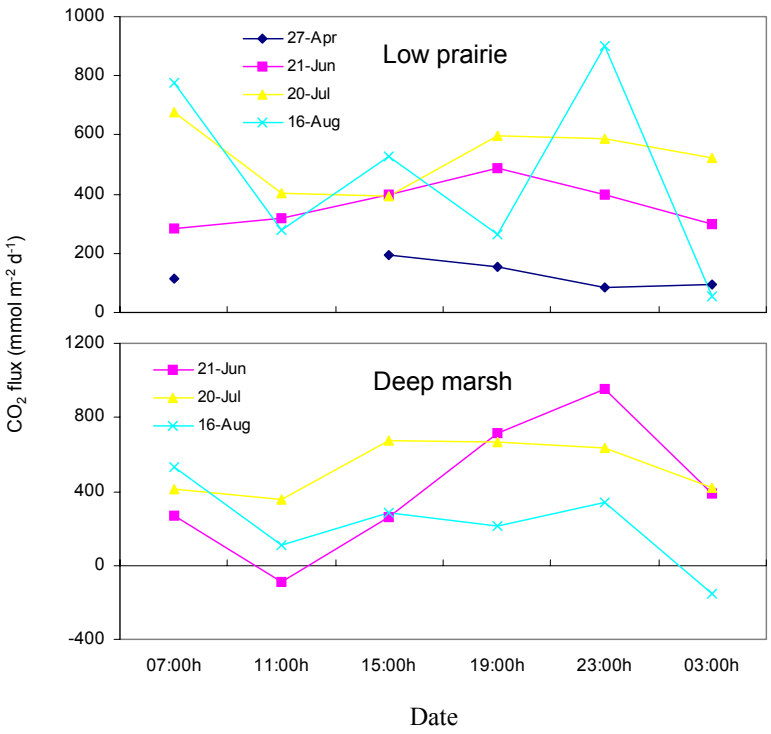


Figure 5.12 Diurnal respiration rates for the Low Prairie (n=3) and Deep Marsh (n=2) segment (2006)

### 5.6 Seasonal $CO_2$ fluxes: Stacking chambers

In 2005 a third type of chamber was used in the Low Prairie zone (the transect was parallel with R1, R2 and R3 of the 2006 large chamber transect). These chambers were stackable, so that the chambers could grow as the plants did. In comparison, the small soil respiration chambers contained little to no vegetation where as the stacking chambers allowed such growth and captured much larger emissions (Figure 5.13). The seasonal trend measured with these chambers showed larger emissions in the spring and early summer than the small respiration chambers. They also captured a different seasonal pattern. The stacking chambers show a period of high emissions from the end of June to mid-August. The small

chambers, on the other hand, start with large emissions in early June which slowly decrease until the end of the summer where they plateau at a low consistent emission rate. These stacking chambers essentially measure the same thing as the large opaque chambers but over a smaller footprint. This allows us to directly assess the influence of riparian vegetation on respiration fluxes. Thus, the inclusion of vegetation from riparian areas appears to be important. The small chambers may underestimate total emissions if gas is emitted from the vegetation itself, as is proving true with these chambers.

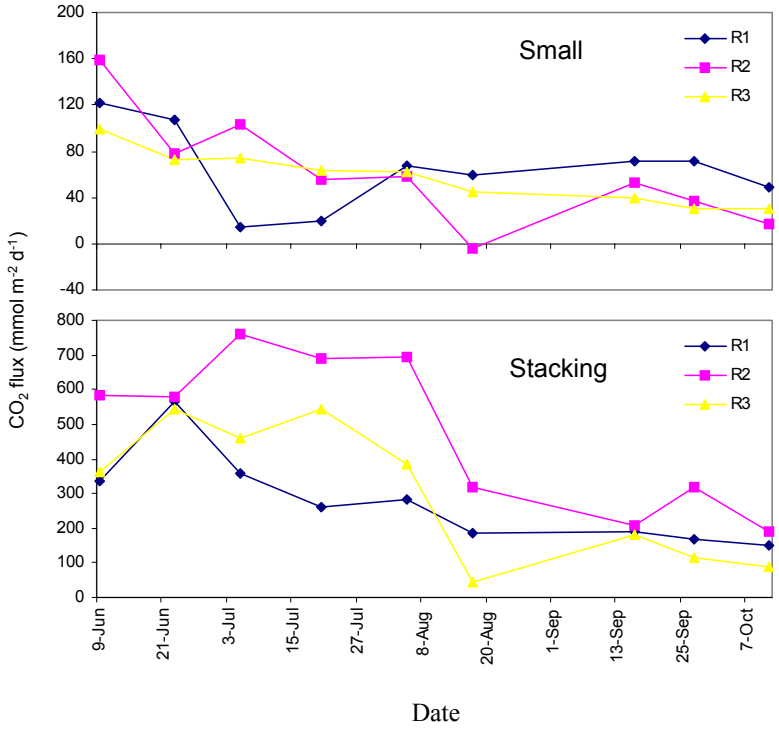


Figure 5.13 Stacking chambers measuring respiration (2005)

## 5.7 Summary

Emergent vegetation biomass along the Low Prairie zone of the large chamber transect, was greater in the in 2006 than 2005. The single point located in the Deep Marsh zone had a greater biomass in 2005. The emergent vegetation biomass, especially Leaf area index (LAI), can strongly affect $CO_2$ fluxes.

The water table at the riparian-wetland fringe appeared to be more dynamic and respond more to precipitation events than the water table level at the riparian-crop fringe. Although the upland well dried up earlier than the well down-slope, both were dry by mid-August. The well at the wetland-fringe is situated in a topographical depression near the wetland and therefore any changes in the wetland water level and ground water level are going to be more pronounced at that location rather than in the well located at a higher elevation.

Soil temperature was fairly consistent for all points, along the large chamber transect, with the exception of RB which was a couple of degrees cooler at various times throughout the season. Exceptionally high temperatures were also recorded at R1 and RA in early June and may have been due to an increased percentage of exposed soil or measurement/instrument errors. The seasonal soil moisture was highly variable from one point to the next. The two points in the Deep Marsh zone remained saturated for much longer than the points in the Low Prairie zone. RA was particularly prone to re-saturation.

In 2005 the consistent seasonal pattern for all points along the small chamber transect included lower emissions in the spring that increased to a mid-summer peak and decreased thereafter. In 2005 the fluxes were greatest in the Cropped Upland, followed by the Low Prairie then the Deep Marsh zone. In general the 2006 seasonal fluxes were more erratic, and exhibited periods of uptake at various times throughout the growing season. Although there appears to be fundamental differences in the seasonal pattern of soil respiration fluxes from year to year it must also be considered that, that the sampling procedure and methodology can greatly affect the fluxes from these chambers. In 2005 the $CO_2$ uptake experienced sporadically throughout the season may be an indication that there were inaccuracies in chamber clipping. Chamber clipping includes the removal of vegetation prior to sampling, any growth in the chamber (even metaphyton in the floating chambers) can affect the $CO_2$ fluxes as highlighted in Section 5.6. This inconsistency in chamber clipping may have been the cause of the difference in $CO_2$ fluxes at the end of June when fluxes from the Cropped Upland and Low Prairie zone decreased but fluxes from the Deep Marsh peaked. The large efflux from W3 during this time may have also been due to $CO_2$ ebullitions. Other sampling inaccuracies such as improper sealing of the chamber lid and/or disturbance near the chamber can also impact the results. There is also a degree of error associated with the flux

calculations. On the other hand a degree of variability associated with annual changes in environmental conditions and adjacent land use changes between years is inherent of these systems. In general 2006 had lower respiration rates from the Low Prairie and Cropped Upland than 2005.

All points in the Low Prairie zone of the large chamber transect exhibited an independent NEE seasonal pattern. The two points in the Deep Marsh zone had similar seasonal patterns. All points experienced a period of low uptake from late-July to early-August, which was likely due to the lack of precipitation at that time. Uptake was greater from the Deep Marsh zone than the Low Prairie zone. There was no direct correlation between NEE from any point along the large chamber transect and soil moisture, soil temperature, or air temperature.

Respiration along the large chamber transect was similar for both the Deep Marsh zone and the Low Prairie zone. A peak in emissions in mid-June was recorded for on day only and may be erroneous. Besides this spike, respiration fluxes appeared to peak in mid-July. There was no direct correlation between respiration and soil moisture or soil temperature.

Diurnal NEE patterns seen in the Low Prairie and Deep Marsh zone include emissions at night and uptake during the day. In the Low Prairie zone June, July and August samplings had similar uptake and emission magnitudes, while April experienced slight emissions throughout the day. In the Deep Marsh zone June and July samplings had similar patterns while August switched from a sink to a source earlier on in the day and then switched back to a sink earlier as well. Although diurnal respiration rates have been strongly linked to soil temperature in other studies (Carroll and Crill, 1997), it was not the case in this study. An attempt was made to assess the net source/sink functioning of the large chamber transect based on the diurnal data; however, the lack of data produced results with a high degree of error. Based on what information was available it is possible that the large chamber transect was a $CO_2$ sink in June, July and August and a source in April.

The seasonal trend from the stacking chambers showed larger emissions in the spring and early summer than the small respiration chambers. The stacking chambers measured a different seasonal pattern than the small chambers. Although the peak fluxes occur early on in the season for both chamber types, flux magnitudes drop in the early summer according to

the small chambers and in mid-August according to the stacking chambers. The paired stacking and small chambers allows us to directly evaluate the importance of riparian vegetation on respiration fluxes measure on this scale. From this study it is evident that the inclusion of vegetation in the chamber footprint is important for the evaluation of respiration from riparian areas.

# 6.0 INTEGRATION OF RESULTS AND CONCLUDING REMARKS

Wetlands are very valuable ecosystems as they play an integral role in wildlife habitat, water management and greenhouse gas exchange. The exchange of carbon dioxide between wetlands and the atmosphere has been studied primarily in northern wetlands. These wetlands, however, behave much differently than prairie pothole wetlands because of fundamental differences in soil type, vegetation cover and hydrology and climatic conditions. More information is needed on the annual exchange of carbon dioxide from prairie pothole wetlands in relation to environmental variables, wetland biology and biogeochemical processes. Restated, the primary objective of this study is to identify rates and trends in the ice-free seasonal carbon dioxide flux from the riparian zone and open-water zone of a prairie pothole wetland, and to relate observed variation in the exchange to characteristics of the wetland's biological, biochemical and hydrometeorological state. Sub-objectives are the characterization of carbon exchange dynamics within the open-water zone of the wetland, and it's riparian fringe.

## 6.1 Review of salient issues relating to carbon dynamics of the wetland complex

### 6.1.1 General climatology

The climatic conditions and biotic factors of the study site varied from 2005 to 2006. Although both years had seasonal temperatures close to the climate normal, the 2005 growing season was slightly cooler than 2006. In terms of precipitation, the 2005 growing season was wetter in May, June and July, but dryer in August and September. In 2006 exceptionally arid conditions in July occurred when precipitation events were significantly less than the climate normal.

### 6.1.2 In-situ pond processes

The difference in ecosystem functioning between years was observed in 3 major ways: algal chlorophyll-*a* concentrations; water biogeochemistry; and lastly in $CO_2$ exchange both from the riparian zone and pond.

Generally greater algal chlorophyll-*a* concentrations were observed in 2005, with the exception of early season chlorophyll-a associated with phytoplankton. Seasonal algal production in 2005 tended to increase throughout the growing season, while production in 2006 experienced a shift in the relative contributions of chlorophyll-*a* from the different algal assemblage. The algal assemblages tended to decreased around mid-summer, with the exception of epiphyton which had, on one occasion in mid-August, relatively high chlorophyll-*a* concentrations. Besides decreasing in chlorophyll-a content, metaphyton presence decreased between mid-July and early-September at which point a new form of metaphyton presented itself.

Information on chlorophyll-*a* highlights fundamental differences in ecosystem functioning between the two years. Factors that may have contributed to the lower chlorophyll-*a* concentrations in 2006 include: an increase in DOC which may have limited light availability; a lack of precipitation in July, and possibly even the influx of algae suppressing chemicals such as herbicides from the adjacent farmland (supported by anecdotal evidence).

The early season (May and June) DOC concentrations in the wetland were very low in 2005 and increased considerably in August, reaching 139.7 mg/L. This increase in DOC may be due to a number of factors including a decrease in water level and macrophyte and metaphyton senescence. External inputs may have also contributed to the increase and may have included organic matter inputs from the surrounding farmland as well as inputs from the large duck population inhabiting the wetland. The DOC increased throughout the 2006 growing season from 30.2 to 51.7 mg/L. Due to the fact that the 2006 season began with higher DOC concentrations the 2005 season it is likely that the high DOC values from August of 2005 were maintained, to a certain degree, over the winter.

Differences in water biogeochemistry between years are likely due to the hydrology of the wetland and the surrounding land use. The higher salinity in 2006 may have been due to the lower water levels, and the higher pH in 2005 may be due to greater in-pond production (as predicted by the higher chlorophyll-*a* concentrations). Higher production involves the removal of dissolved $CO_2$, and results in the consumption $H^+$ ions which in-turn increases the pH of the system. During the summer of 2005 pH values were higher than in 2006 and the water was less saline.

In 2005 episodic increases in DO were likely due to the high algal turnover, this includes production which increases DO and decomposition decreases DO. In 2006 DO decreased over time, which is consistent with the increase in DOC over time (as the availability of DOM increases the rate of decomposition of DOM and results in decreased DO levels).

Carbon dioxide fluxes from the pond proper followed different seasonal patterns between years. In fact the years were almost the reverse of each other. While 2005 displayed low emissions during the early spring and high emissions during senescence, 2006 had large emissions in the early spring and low emissions or uptake during senescence. The net efflux that is suspected to have occurred over the 2005 and 2006 growing season is concurrent with other littoral zones under similar climatic conditions, which have been found to evade $CO_2$ over the growing season (Sellers et al., 1995, Duchemin et al., 1999, Matthews et al., 2003). This occurs when respiration, and organic matter decomposition exceeds productivity producing $CO_2$ saturated waters.

In 2006 there was a strong diurnal $CO_2$ flux pattern from the pond proper for all four periods, which consisted of lower $CO_2$ emissions during the day and higher $CO_2$ emissions at night. Presumably the lower efflux during the daytime period is because of photosynthetic uptake during the high sun period. In 2005 a diurnal $CO_2$ pattern was only present for the third period. Although no direct inverse correlation was found between the diurnal pattern of $CO_2$ and DO, it is evident that as DO tended to migrate in the opposite direction as the $CO_2$ diurnal pattern.

The high $CO_2$ effluxes that were observed in the spring of 2006 may have been due to a warm spring which promoted decomposition. It may also have been due to the

decomposition of OM which may have built up over the winter (plant material in ponds die over the winter, but do not start to decompose until the spring), and/or continued over from high August 2005 levels. There simply may not have been as much organic matter present in 2005 to decompose.

Strikingly similar seasonal patterns between $CO_2$ fluxes and DOC levels may be able to highlight the importance of this relationship. Recall, DOC levels in the pond were low throughout the growing season of 2005 and increased in late August (during senescence). This is also true for the $CO_2$ fluxes from the pond, which increased in early September. This linkage between the seasonal patterns of DOC and $CO_2$ fluxes is also seen in 2006. In 2006 the higher early season DOC levels mimic a general increase in $CO_2$ efflux. The amount of DOC likely impacts the $CO_2$ fluxes by suppressing algal photosynthesis (by limiting light penetration) and through decomposition. It is likely that the DOC suppressed algal chlorophyll-*a* concentration in 2006.

### 6.1.3 In-situ riparian zone processes

The water table level at the riparian–wetland fringe (measured in 2006) appeared to be more dynamic and have a greater response to precipitation events than the water table level at the riparian-crop fringe. This highlights the influence of landscape position, vegetation and soil type on water table dynamics. Although the upland well dried up (i.e., the water table level surpassed a depth of 100 cm) earlier on in the season than the well down-slope (which is to be expected because of the proximity to the water body) both wells were dry by mid-August.

The soil temperature along the large chamber transect followed a fairly consistent seasonal pattern (gradually peaking in late-June and descending thereafter), with the exception of RB (the wettest point) which was a couple of degrees cooler at various times thorough out the season. Exceptionally high temperatures were measured at R1 (the most upland point) and RA (the most inland point in the Deep Marsh) in early-June and may be erroneous. On the other hand, soil moisture was highly variable for all points along the

transect. The two points in the Deep Marsh zone remained saturated for much longer than the points in the Low Prairie zone. RA was particularly prone to re-saturation.

Respiration was measured in 2005 with small soil chambers and showed a consistent seasonal pattern for all points along the transect. This seasonal pattern included lower emissions in the spring, which increased to a mid-summer peak and decreased thereafter. In 2006 the small chamber seasonal respiration pattern was more erratic. In 2005 the respiration fluxes increased upslope (when averaging the points within the landscape zones).

The seasonal NEE patterns of the three points in the Low Prairie zone measured by the large clear chambers were highly independent of one another. The two points in the Deep Marsh zone, however, had similar seasonal patterns. Respiration fluxes in the Low prairie and Deep Marsh zone peaked in mid-July, with the exception of a spike which occurred in mid-June. Diurnal NEE patterns seen in the Low Prairie and Deep Marsh zone includes emissions at night and uptake during the day, which is concurrent with plant photosynthesis and respiration. In the low prairie zone the June, July and August samplings had similar magnitudes of uptake and emission, while April exhibited low emissions throughout the day.

The canopy-scale chambers that measured NEE had a high degree of variability within the Low Prairie zone, which is likely the result of the observed vegetation gradient through the riparian fringe and into the pond. The lack of variation of vegetation in the Deep Marsh zone resulted in a similar NEE from the two points. This sampling technique found that uptake was generally greater from the Deep Marsh zone than the Low Prairie zone.

Although soil temperature and moisture have been linked to soil respiration in other studies, no direct correlation was found in this study. However, the lack of precipitation during the month of July in 2006 (during this time the study sited received a little more that one tenth of the average precipitation for this area) appeared to have impacted the vegetation in the riparian zone by making them water stressed and thus decreasing photosynthesis. Observations using the canopy-scale chambers highlight this by showing that all points experienced a decrease in $CO_2$ uptake from late-July to early-August.

The diurnal NEE and respiration patterns were similar to those from other studies (Sims and Bradford, 2001 and Bonneville et al., 2008). The low $CO_2$ emissions in April were likely due to lack of plant growth (and thus photosynthesis) and instead dominated by

microbial/soil respiration, and decomposition of any residual organic matter. June and July had similar diurnal patterns in the Deep Marsh zone (uptake during the day and emissions at night). In August the system switched from sink to source earlier in the day relative to the pattern observed in June and July. The observed difference in August may be associated with general surface climate (i.e., lower temperatures and shorter daylight hours). It appears that the area serves as a carbon sink in June, July and August and a source in April.

The soil respiration chambers measured very different season patterns in $CO_2$ fluxes over the two years. In 2006 the $CO_2$ fluxes were greatest in the Cropped Upland, followed by the Low Prairie then Deep Marsh zone. This was not as evident in 2006. The difference in the seasonal patterns between years may be due to the inherent variability within the ecosystem from year to year, or as previously discussed, may be a result of inherent biases associated with the deployment of soil respiration chambers. It is clear that our understanding of the source/sink characteristics of the riparian zone would be very different had canopy-scale chambers not been deployed.

### 6.2 The wetland complex

The riparian zone was $CO_2$ sink over the 2006 during the hours of peak productivity (as measure by the canopy-scale NEE chambers). On the other hand results presented here indicate that the open water zone was a source of $CO_2$ for most of the growing season. Interestingly, soil respiration (measured with the small respiration chambers) was greater from the riparian zone than from the open water zone (W3). Phipps (2006) also showed that the $CO_2$ emissions from soils adjacent to the pond were greater than from the pond itself. Results presented here however indicate that growing season photosynthesis from the riparian vegetation is in excess of soil respiration.

As mentioned at the onset of this work, wetland complexes are prevalent landscape features within a large proportion of the Northern Great Plains. It is a useful exercise to understand the role of the pond and fringe within the landscape, given the observed differences in uptake/emission characteristics and propensity for changing areal proportions with variations and change in climate.

On average we observe an efflux of 25 mmol $CO_2$ $m^{-2}d^{-1}$ from the pond, based on the continuous $CO_2$ fluxes from the pond for periods I, II and III in 2006. Estimates of $CO_2$ exchange during the growing season in the riparian zone (or Low Prairie zone) and cattail zone (or Deep Marsh zone) are -78 and -50 mmol $CO_2$ $m^{-2}d^{-1}$ (respectively). The area of open water, Low Prairie and Deep Marsh occupying the Manitoba Zero-Tillage Research Association's section of farmland is shown in Table 6.1 (Renard and Lobb, 2004). Wetland complexes constitute approximately 50% of the experimental farm. By weighting the average rate of daily $CO_2$ exchange by the proportional area coverage (Table 6.1), our results show the wetland ecosystem could sequester approximately 2311 mol $CO^2$ $d^{-1}$ between April and August – the heart of the region's growing season. Frank and Dugas (2000) estimated the NEE for a temperate grassland ecosystem in the Northern Great Planes from April 24$^{th}$ to October 26$^{th}$. The seasonal average NEE for this period was -42.3 mmol $CO_2$ $m^{-2}d^{-1}$. If we assume that this system is similar to that of the cropped upland, the cropped land on the farm would sequester -54,230 mol $CO_2$ $d^{-1}$. All together the entire farmland would sequester 56,541 mol $CO_2$ $d^{-1}$. Given our observations from 2005 and 2006, it is possible that this ecosystem may become a stronger carbon sink in wetter years considering that production within the pond will likely increase and $CO_2$ emissions will likely decrease.

Table 6.1 Area of wetland zones on the Manitoba Zero-Tillage Research Association Farm (data from Renard and Lobb, 2004)

| Zone | Area ($1000m^2$) | Percentage of Farm |
|---|---|---|
| **Riparian Zone** | 65.6 | 2.5% |
| **Cattails Zone** | 376.5 | 14.5% |
| **Water Zone** | 865.2 | 33.4% |
| **Total** | 1307.3 | 50.5% |

### 6.3 An assessment of knowledge gaps and future research needs

The results presented from this two-year study demonstrate the potential for inter-annual variation in carbon cycling within Prairie Pothole wetlands. Observed variation appears related to local water balance conditions. It is difficult to anticipate the response of these systems to a changing climate. However, given model forecasts of generally warmer and drier conditions we can expect larger wetland complexes to shrink and smaller ones to dry up. The drying of wetlands and subsequent conversion to agriculture will likely result in a loss of $CO_2$. The shrinking of wetlands may result in an increase in DOC in the water column. As seen in this study, increased DOC levels may produce a greater evasion of $CO_2$ from the pond proper. In addition, an increase in temperature and UV radiation can greatly limit algal production. The riparian zone will likely shrink in overall area in correspondence with the open water. Higher temperatures and less precipitation can stress the riparian vegetation and limit photosynthesis, as seen in this study.

To better understand the effects of climate change on the functioning of Prairie Pothole wetland ecosystems, more information is needed on the relationships between hydrometeorology and $CH_4$, $N_2O$ and $CO_2$ fluxes from these wetlands. A better understanding is also required of the relationship between wetland biology and trace gas exchange. Future work should include the development of these relationships for the advancement of wetland modeling in order to help predict future greenhouse gas exchange under a changing climate.

Little is known about the overall functioning of the riparian zone of prairie wetlands in terms of greenhouse gas emissions. It is unknown how the management practices on the adjacent uplands, hydrology and environmental factors effects these processes. Future work should include usage of the canopy-scale NEE chambers for numerous diurnal samplings throughout the growing season, in order to accurately assess the net $CO_2$ exchange with in the riparian zone. It would also be useful to sample for $CH_4$ and $N_2O$ to get a comprehensive idea of the greenhouse gas exchange from this zone.

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# 8.0 APPENDIX A

Continuous Aquatic $CO_2$ sampler program

```
;{CR10X}
;This program runs the CEOS Mark I CO2 box.
;User must enter a time of day (in minutes) to start the process
;Edit time in instructions 4 and 5.
;
;Measurement sequence starts on the hour.
; 5min air
; 10min water
; 10min water
; 5min air
; 1min reverse
; shut-down
;
; Program sequence:
; 15 min to hour, irga turned on
; start of hour, sample air
; 5 min after hour record air sample start water pump
; 15 min after hour record 1st water sample
; 25 min after hour record 2nd water sample start 2nd air sample, stop the
flush water pump
; 27 min after hour shut off water pump
; 30 min after record 2nd air sample, shut down system (except logger)
;
; Output array IDs as follows
; 300 1st output for air temperature
; 301 1st output for water temperature
; 302 2nd output for water temperature
; 303 2nd output for air temperature
;

;Port usage
;C3 on/off switch for valve chip high=on
;C4 toggles solenoid valve low=air high=water
;C5 starts the irga:  high = start
;C6 toggles the water pump: low=reverse high=forward
;C7 starts the water pump: high=on low=off
;C8 starts the air pump: high=on low=off

*Table 1 Program
  01: 10        Execution Interval (seconds)


; battery voltage
1:  Batt Voltage (P10)
 1: 3        Loc [ batt      ]

;CO2 from Licor via DAC2 channel 9 and 10 on the Licor 820
;output in ppm based on 2000ppm range and 2.5V output range (see manual pg
3-10)
;2 high to port 7 on the Licor 820, 2 Low to port 8 on the 820

2:  Volt (Diff) (P2)
```

```
 1: 1        Reps
 2: 5        2500 mV Slow Range
 3: 2        DIFF Channel
 4: 1        Loc [ co2       ]
 5: .8       Mult
 6: 0.0      Offset

;cell pressure from Licor 820 via DAC1 channel 7 and 8 on licor
;output in kPa based on 2.5V output range (see manual pg 3-10)
;2 high to port 9 on the Licor 820, 3 Low to port 10 on the 820

3:  Volt (Diff) (P2)
 1: 1        Reps
 2: 5        2500 mV Slow Range
 3: 3        DIFF Channel
 4: 2        Loc [ cell_pres ]
 5: .046     Mult
 6: 0.0      Offset

; Measure the water temperature and case temperature
4:  Temp (107) (P11)
 1: 1        Reps
 2: 7        SE Channel
 3: 3        Excite all reps w/E3
 4: 4        Loc [ Tw        ]
 5: 1.0      Mult
 6: 0.0      Offset


5:  Thermocouple Temp (DIFF) (P14)
 1: 1        Reps
 2: 14       250 mV Fast Range
 3: 1        DIFF Channel
 4: 1        Type T (Copper-Constantan)
 5: 4        Ref Temp (Deg. C) Loc [ Tw        ]
 6: 5        Loc [ Twater    ]
 7: 1.0      Multiplier
 8: 0.0      Offset

;this instruction is to bypass the tidal on/off switch located in
;the following 2 P92 instructions

6:  Do (P86)
 1: 11       Set Flag 1 High

;USER input according to appliation or comment out if inapplicable.
;set time of day to start (corresponds to start of low tide)

;6:  If time is (P92)
; 1: 945      Minutes (Seconds --) into a
; 2: 1440     Interval (same units as above)
; 3: 11       Set Flag 1 High

;set time of day to stop (corresponds to start of low tide)

;6:  If time is (P92)
; 1: 1439     Minutes (Seconds --) into a
```

```
; 2: 1440     Interval (same units as above)
; 3: 21       Set Flag 1 Low


7:  If Flag/Port (P91)
 1: 11       Do if Flag 1 is High
 2: 30       Then Do

;check for battery voltage, if less than 11.7 no further sampling will
;proceed untill the voltage increases
8:  If (X<=>F) (P89)
 1: 3        X Loc [ batt      ]
 2: 3        >=
 3: 11.7     F
 4: 30       Then Do

;As written, the program will start a measurement sequence on the hour
;First, turn on the gas analyzer prior to the hour mark.

; fifteen minutes before the hour turn on the gas analyzer
9:  If time is (P92)
 1: 45       Minutes (Seconds --) into a
 2: 60       Interval (same units as above)
 3: 30       Then Do


10:  Do (P86)
 1: 45       Set Port 5 High


11:  Set Port(s) (P20)
 1: 7777     C8..C5 = output/output/output/output
 2: 7777     C4..C1 = output/output/output/output


12:  End (P95)


13:  If time is (P92)
 1: 0        Minutes (Seconds --) into a
 2: 60       Interval (same units as above)
 3: 30       Then Do

; start the gas analyzer, in case the program started after the 15 min
mark
     14:  If Flag/Port (P91)
      1: 55       Do if Port 5 is Low
      2: 45       Set Port 5 High

;turn on reverser chip for valves

15:  Do (P86)
 1: 43       Set Port 3 High


; toggle the power (C4) to switch the solenoid valve (assuming low is air)
```

```
     16:  Do (P86)
      1: 54       Set Port 4 Low

;start the air pump

     17:  Do (P86)
      1: 48       Set Port 8 High

; set the co2 flag to 0 when samping air
     18:  Z=F x 10^n (P30)
      1: 0        F
      2: 00       n, Exponent of 10
      3: 6        Z Loc [ CO2Flag   ]


19:  End (P95)

     20:  If time is (P92)
      1: 5        Minutes (Seconds --) into a
      2: 60       Interval (same units as above)
      3: 10       Set Output Flag High (Flag 0)


     21:  Set Active Storage Area (P80)^17523
      1: 1        Final Storage Area 1
      2: 300      Array ID

     22:  Real Time (P77)^3325
      1: 220      Day,Hour/Minute (midnight = 2400)

     23:  Sample (P70)^10996
      1: 6        Reps
      2: 1        Loc [ co2       ]

;after 5 minutes, start the peri pump for 1st 10 min sample and reverse
the solnoid valve
     24:  If time is (P92)
      1: 5        Minutes (Seconds --) into a
      2: 60       Interval (same units as above)
      3: 30       Then Do

;make sure that the irga is on

     25:  If Flag/Port (P91)
      1: 55       Do if Port 5 is Low
      2: 45       Set Port 5 High

;start the peri pump
          26:  Do (P86)
           1: 47       Set Port 7 High

;water pump in forward

27:  Do (P86)
 1: 46       Set Port 6 High
```

```
;set the solenoid in its forward position (assuming that this is when port
4 is high)

          28:  Do (P86)
           1: 44       Set Port 4 High

;set the co2 flag to 1 when samping water
          29:  Z=F x 10^n (P30)
           1: 1        F
           2: 0        n, Exponent of 10
           3: 6        Z Loc [ CO2Flag   ]


     30:  End (P95)


;output 1st water measurement after 10min equilibration
          31:  If time is (P92)
           1: 15       Minutes (Seconds --) into a
           2: 60       Interval (same units as above)
           3: 10       Set Output Flag High (Flag 0)

          32:  Set Active Storage Area (P80)^28321
           1: 1        Final Storage Area 1
           2: 301      Array ID

          33:  Real Time (P77)^4022
           1: 220      Day,Hour/Minute (midnight = 2400)

          34:  Sample (P70)^11344
           1: 6        Reps
           2: 1        Loc [ co2       ]


;start the 2nd 10 m water sample

     35:  If time is (P92)
      1: 15       Minutes (Seconds --) into a
      2: 60       Interval (same units as above)
      3: 30       Then Do

;irga on?
     36:  If Flag/Port (P91)
      1: 55       Do if Port 5 is Low
      2: 45       Set Port 5 High

;air pump on?
     37:  If Flag/Port (P91)
      1: 58       Do if Port 8 is Low
      2: 48       Set Port 8 High

; water pump on?
     38:  If Flag/Port (P91)
      1: 57       Do if Port 7 is Low
      2: 47       Set Port 7 High

;solenoid in the correct position?
```

```
     39:  If Flag/Port (P91)
      1: 54       Do if Port 4 is Low
      2: 44       Set Port 4 High

;set the co2 flag to 1 when samping water
          40:  Z=F x 10^n (P30)
           1: 1        F
           2: 0        n, Exponent of 10
           3: 6        Z Loc [ CO2Flag   ]

     41:  End (P95)

               42:  If time is (P92)
                1: 25       Minutes (Seconds --) into a
                2: 60       Interval (same units as above)
                3: 10       Set Output Flag High (Flag 0)

               43:  Set Active Storage Area (P80)^2748
                1: 1        Final Storage Area 1
                2: 302      Array ID

               44:  Real Time (P77)^10388
                1: 220      Day,Hour/Minute (midnight = 2400)

               45:  Sample (P70)^14190
                1: 6        Reps
                2: 1        Loc [ co2       ]


;end the 2nd 10 m water sample, clean pump and re-start air sampling

               46:  If time is (P92)
                1: 25       Minutes (Seconds --) into a
                2: 60       Interval (same units as above)
                3: 30       Then Do

;make sure that the irga is on

                    47:  If Flag/Port (P91)
                     1: 55       Do if Port 5 is Low
                     2: 45       Set Port 5 High

;reverse the water pump

                    48:  Do (P86)
                     1: 56       Set Port 6 Low

;reverse the solenoid valve
                    49:  Do (P86)
                     1: 54       Set Port 4 Low

;air pump on?

                    50:  If Flag/Port (P91)
                     1: 58       Do if Port 8 is Low
                     2: 48       Set Port 8 High
```

```
;set CO2 flag to 0

                    51:  Z=F x 10^n (P30)
                     1: 0.0      F
                     2: 00       n, Exponent of 10
                     3: 6        Z Loc [ CO2Flag   ]

               52:  End (P95)

;stop the water pump

53:  If time is (P92)
 1: 27       Minutes (Seconds --) into a
 2: 60       Interval (same units as above)
 3: 57       Set Port 7 Low


;after 5 minutes take average air concentration

                    54:  If time is (P92)
                     1: 30       Minutes (Seconds --) into a
                     2: 60       Interval (same units as above)
                     3: 10       Set Output Flag High (Flag 0)

                    55:  Set Active Storage Area (P80)^15102
                     1: 1        Final Storage Area 1
                     2: 303      Array ID

                    56:  Real Time (P77)^20883
                     1: 220      Day,Hour/Minute (midnight = 2400)

                    57:  Sample (P70)^28059
                     1: 6        Reps
                     2: 1        Loc [ co2       ]

;stop the air pump


                    58:  If time is (P92)
                     1: 30       Minutes (Seconds --) into a
                     2: 60       Interval (same units as above)
                     3: 30       Then Do

; stop the air pump

                         59:  Do (P86)
                          1: 58       Set Port 8 Low


                    60:  End (P95)


;shut the system down
                         61:  If time is (P92)
                          1: 30       Minutes (Seconds --) into a
                          2: 60       Interval (same units as above)
                          3: 30       Then Do
```

```
;turn all ports low

62:  Set Port(s) (P20)
 1: 0000     C8..C5 = low/low/low/low
 2: 0000     C4..C1 = low/low/low/low


                         63:  End (P95)

                    64:  End (P95)

               65:  End (P95)




*Table 2 Program
  02: 0.0000    Execution Interval (seconds)

*Table 3 Subroutines

End Program


-Input Locations-
1 co2       5 4 1
2 cell_pres 9 4 1
3 batt      9 5 1
4 Tw        5 5 1
5 Twater    1 0 1
6 CO2Flag   1 3 4
7 __________ 0 0 0
8 __________ 0 0 0
9 __________ 0 0 0
10 __________ 0 0 0
11 __________ 0 0 0
12 __________ 0 0 0
13 __________ 0 0 0
14 __________ 0 0 0
15 __________ 0 0 0
16 __________ 0 0 0
17 __________ 0 0 0
18 __________ 0 0 0
19 __________ 0 0 0
20 __________ 0 0 0
21 __________ 0 0 0
22 __________ 0 0 0
23 __________ 0 0 0
24 __________ 0 0 0
25 __________ 0 0 0
26 __________ 0 0 0
27 __________ 0 0 0
28 __________ 0 0 0
-Program Security-
```

```
0000
0000
0000
-Mode 4-
-Final Storage Area 2-
0
-CR10X ID-
0
-CR10X Power Up-
3
-CR10X Compile Setting-
3
-CR10X RS-232 Setting-
-1
-DLD File Labels-
0
-Final Storage Labels-
0,300,17523
1,Day_RTM,3325
1,Hour_Minute_RTM
2,co2~1,10996
2,cell_pres~2
2,batt~3
2,Tw~4
2,Twater~5
2,CO2Flag~6
3,301,28321
4,Day_RTM,4022
4,Hour_Minute_RTM
5,co2~1,11344
5,cell_pres~2
5,batt~3
5,Tw~4
5,Twater~5
5,CO2Flag~6
6,302,2748
7,Day_RTM,10388
7,Hour_Minute_RTM
8,co2~1,14190
8,cell_pres~2
8,batt~3
8,Tw~4
8,Twater~5
8,CO2Flag~6
9,303,15102
10,Day_RTM,20883
10,Hour_Minute_RTM
11,co2~1,28059
11,cell_pres~2
11,batt~3
11,Tw~4
11,Twater~5
11,CO2Flag~6
```