CO₂ exchange in a subarctic sedge fen in the Hudson Bay Lowland during two consecutive growing seasons

by

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ABSTRACT

Net ecosystem carbon dioxide exchange (NEE) was measured using the eddy covariance (EC) technique at a wetland tundra-sedge fen near Churchill, Manitoba, Canada during two consecutive growing seasons (2007 and 2008). Mean daily NEE at the fen (DOY 157-254) was -3.5 (± 0.26 S.E.) g CO$_2$ m$^{-2}$ d$^{-1}$ in 2007 and -4.6 (± 0.36) g CO$_2$ m$^{-2}$ d$^{-1}$ in 2008. The fen was a net carbon dioxide (CO$_2$) sink during both the 2007 and 2008 growing seasons of -343 (± 79) and -450 (± 87) g CO$_2$ m$^{-2}$, respectively. Mean air temperature during the summer (June 1-August 31) was about 1°C greater than the historical average (1971-2000) in 2007 and about 2°C greater in 2008. Growing season precipitation was 107.5 mm below normal in 2007 and 359.5 mm above normal in 2008. These data suggest that if future climate change brings warmer temperatures and near-to-above average precipitation maintaining the water table near the surface, similar subarctic ecosystems will experience increased gross ecosystem productivity enhancing CO$_2$ sequestration during the growing season.
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ABBREVIATIONS

CO₂: carbon dioxide  
CST: central standard time  
DOY: day of year  
EBC: energy balance closure  
EC: eddy covariance  
EF: evaporative fraction  
ER: ecosystem respiration  
Eₜ: evapotranspiration  
ETₚₑₜ: equilibrium rate of evapotranspiration  
ETₜₒₜ: total evapotranspiration  
GEP: gross ecosystem carbon dioxide exchange  
GEPₚₘₐₓ: photosynthetic capacity for unlimited photosynthetic photon flux density  
HBL: Hudson Bay Lowland  
JJA: June, July, and August  
LAI: leaf-area index  
N/A: not available  
NEE: net ecosystem carbon dioxide exchange  
OFF: offshore winds  
ON: onshore winds  
PPFD: photosynthetic photon flux density  
Pₚₒₜ: total precipitation  
Q: net radiation  
Q₁₀: relative increase in modelled ecosystem respiration 10°C greater than R₁₀  
Qₑ: latent heat flux  
Qₒ: ground heat flux  
Qₜ: sensible heat flux  
R₁₀: modelled ecosystem respiration at a reference temperature of 10°C  
r²: coefficient of determination  
RH: relative humidity  
S.D.: standard deviation  
S.E.: standard error  
Ta: air temperature  
Ta_avg: average air temperature  
Ta_max: mean maximum air temperature  
Ta_mean: historic normal air temperature (1971-2000)  
Ta_min: mean minimum air temperature  
Ts: soil temperature  
Ts_max: maximum soil temperature  
Ts_min: minimum soil temperature  
u*: friction velocity  
VPD: vapour pressure deficit  
WT: water table height
WTD: water table depth
WUE: water use efficiency
α: apparent light-use efficiency
α_{PT}: Priestley-Taylor evaporation coefficient
β: Bowen ratio
ΣER: cumulative ecosystem respiration
ΣGDD: cumulative growing degree-days
ΣGEP: cumulative gross ecosystem carbon dioxide exchange
ΣNEE: cumulative net ecosystem carbon dioxide exchange
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SECTION 1: INTRODUCTION

1.1 Background

Northern wetlands cover approximately 3% of the global land surface but constitute about 30% of total soil organic carbon (Gorham, 1991), equivalent to about half the carbon in the atmosphere, evidencing their importance to the global carbon cycle as a sink of atmospheric CO₂. Since the last glaciation, carbon accumulation has occurred due to inhibited rates of decomposition caused by low temperatures and anaerobic conditions associated with high water tables (Clymo 1984, 1992, 1998) and inherent slow rates of litter decomposition (Johnson and Damman, 1993; Verhoeven and Toth, 1995; Moore et al., 2007). Peat accumulation occurs because litter inputs are greater than outputs (i.e. peat accumulation > peat decomposition; Vitt et al., 2009). General circulation models predict high latitude regions will experience warming and decreased soil moisture (ACIA, 2005; IPCC, 2007), causing concern over the vulnerability of this carbon store because of climate change (Oechel et al., 1993, 1995, 1998, 2000; Chapin et al., 2005; Vourtilis and Oechel, 1997; McGuire et al., 2000, 2009; Schuur et al., 2008) and potential feedbacks on the climate system (Bridgeham et al., 1995; Moore et al., 1998; Frolking et al., 2006).

Subarctic wetland regions are predicted to experience pronounced effects of climate change (Tarnocai, 2006). Climatic warming has the potential to diminish CO₂ sequestration through increased rates of peat decomposition associated with higher
temperatures and increased aeration of peat (Oechel et al., 1998). Conversely, higher temperatures and increased aeration of peat will lengthen the growing season and increase nutrient mineralization (Bridgeham et al., 1998; Mikan et al., 2002), changing vegetation distribution (Belyea and Malmer, 2004), augmenting productivity, and possibly offsetting any increase in the rate of decomposition (Welker et al., 2004; Lund et al., 2009). Many northern peatlands are nutrient-limited ecosystems that often experience increased carbon sequestration from increased nutrient availability (Shaver et al., 1986, 1995, 1998; Johnson et al., 2000). Furthermore, ecosystem respiration (ER) during the long winter season, also expected to increase with warming temperatures, can potentially exceed growing season CO₂ uptake (Oechel et al., 1997; Fahnestock et al., 1999). Drought can impact the CO₂ balance of these northern wetlands through increased ER and decreased gross ecosystem productivity (GEP) (Moore et al., 1993; Schreader et al., 1998; Moore et al., 1993; Alm et al., 1999; Aurela et al., 2007). Permafrost thaw will also impact the CO₂ balance of these northern wetlands through increased ER and GEP (Camill et al., 2001; Christensen et al., 2004; Schuur et al., 2009).

Since the most recent glaciation, peatlands have been historical net-CO₂ sinks evidenced by their accumulation of organic matter; however, the systems' net ecosystem CO₂ exchange has been observed to vary from net sink to source over varying timescales. Wet sedge fens can sequester large amounts of CO₂ over the course of a growing season (Nobrega and Grogan, 2008). Interannual peatland CO₂ exchange however can vary substantially (Lafleur et al., 2001, 2003; Groendahl et al., 2007; Aurela et al., 2004, 2009) sometimes becoming a net-CO₂ source (Oechel et al., 1993; Shurpali et al., 1995; Griffis
et al., 2000a). Environmental controls often have confounding effects on the variation of NEE depending on ecosystem type (Walker et al., 2006; Oberbauer et al., 2007; Starr et al., 2008). Shurpali et al. (1995) found CO₂ exchange during two consecutive growing seasons in a Minnesota peatland to be a function of moisture and temperature conditions, with inhibited productivity and enhanced respiration during conditions of moisture stress and higher temperatures. Carbon dioxide exchange studies conducted at a wet sedge tundra site in Northern Alaska suggest that low air temperatures and high solar radiation immediately following spring thaw contributed to faster vegetation development leading to higher CO₂ uptake (Harazono et al., 2003). Harazono et al. (2003) did not find water content within the peat profile to be a major factor on CO₂ exchange. Another Alaskan study at a similar wet sedge tundra site summarizing five years of growing season data indicated that the effect of air temperature on net ecosystem CO₂ exchange (NEE) was variable (Kwon et al., 2006). Kwon et al. (2006) calculated high CO₂ uptake in early-June of 2002 and attributed it to the early onset of snowmelt which increased photosynthetic capacity through early plant development and inhibited rates of ER due to frozen soil temperatures. Research conducted at a subarctic sedge fen in the Hudson Bay Lowland (HBL) also found spring hydroclimatic conditions to be important to the growing season CO₂ balance (Griffis et al., 2000b; Griffis and Rouse, 2001). Griffis and Rouse (2001) found interannual growing season NEE variation to be driven more by changes in GEP rather than ER. A three year study conducted over low Arctic tundra in central Canada found net-CO₂ uptake controlled mainly by temperature and water availability, driven by changes in GEP rather than ER (Lafleur and Humphreys, 2007). In contrast, variation in interannual NEE of Alaskan tussock tundra was found to be
driven more by changes in ER rather than changes in GEP (Vourlitis and Oechel, 1999; Kwon et al., 2006), highlighting the importance of ecosystem differences within these tundra environments on interannual variations in NEE. A comprehensive regional study of Alaskan tundra environments found regional variation to be largely driven by GEP and not ER (McFadden et al., 2003). A multi-year CO$_2$ exchange study in Finland at a rich fen indicated photosynthetic capacity of the vegetation as the most important determinant on the CO$_2$ balance (Aurela et al., 2009). Aurela et al. (2009) attributed the low CO$_2$ uptake in 2006 to warm and dry conditions during the growing season which inhibited vegetation development. Another multi-year CO$_2$ exchange study in Finland at a different rich fen site showed that the timing of snow melt was the single most important factor in determining the CO$_2$ balance (Aurela et al., 2004). An earlier snow melt and warmer spring time conditions did not seem to influence more southerly locations the same (Moore et al., 2006). Aurela et al., (2004) also found no correlation between many hydrometeorological variables throughout the growing season and the annual CO$_2$ balance. Bubier et al. (1998) also found the timing of snow melt to be an important factor on the CO$_2$ balance of diverse peatland complex in Northern Manitoba along with soil temperature above the water table and the timing of freeze-up. A comprehensive study of European arctic ecosystems found leaf-area index (LAI) to be the most important factor in determining GEP (Laurila et al., 2001). A study of four different Scandinavian mires found monthly averages of GEP and ER to be strongly dependent on water table depth (WTD) during drying periods (Lindroth et al., 2007). Lindroth et al. (2007) found a strong correlation between ER and GEP indicating that the majority of ER can be attributed to autotrophic respiration. They also found temperature sensitivity to be
greatest for GEP rather than for ER indicating that CO₂ uptake increased with temperatures. A five-year CO₂ exchange study of a large dry ombrotrophic bog near Ottawa, Canada found daily averages of ER to correlate with soil temperature (Tₛ) but not WTD (Lafleur et al., 2005). In that study ER from wetter peatlands had a stronger dependence on WTD. The CO₂ balance of a high arctic site in Svalbard was largely controlled by near surface soil temperature and solar radiation (Lloyd, 2001). Lloyd (2001) found precipitation events to be important in maintaining bryophyte photosynthetic activity. Data collected during the growing season of 1996 indicated that a sedge fen in northeast Greenland is currently a net-CO₂ sink and functionally optimally given the current temperature conditions but an increase in temperature of 5°C would turn the sedge fen into a net-CO₂ source (Soegaard and Nordstroem, 1999). However, data collected during the 1997 growing season at the same sedge fen site indicated that the annual CO₂ balance was slightly positive and therefore a CO₂ source (Nordstroem et al., 2001). A five-year CO₂ exchange study of an Arctic heath ecosystem in northeast Greenland found interannual variability of NEE to be largely driven by changes in GEP rather than ER (Groendahl et al., 2007). Groendahl et al. (2007) found the timing of snowmelt, air temperature (Tₘ), and the frequency of rain events as the parameters controlling the CO₂ balance. Rennermalm et al. (2005) analyzed four growing seasons of data from a high arctic fen in northeast Greenland and found LAI development and maximum rubisco capacity as more important controls on the interannual variability of NEE rather than meteorological conditions.
1.2 Churchill Fen Site

Studies conducted at a fen near to Churchill, MB during the 1990s indicate that the fen interannually oscillates from a net-CO₂-sink to a net-CO₂-source, depending on hydroclimatic conditions prior and during the growing season (Schreader et al., 1998; Griffis and Rouse, 2001). Burton et al. (1996) measured mainly net-CO₂ release during the growing season of 1993. Schreader et al. (1998) summarized data collected during an exceptionally warm and dry summer in 1994 and recorded a substantial release of CO₂ from the fen during the growing season and attributed the CO₂ release to inhibited rates of photosynthesis and enhanced rates of respiration. Evidence suggests that subarctic wetland plants conserve water during periods of drought (Blanken and Rouse, 1996), leading to decreased rates of GEP. On the other hand, the high water table at this site has been found to inhibit GEP and it has been predicted that a small decrease in WTD could triple the net-CO₂ uptake of this fen (Griffis et al., 2000b). Furthermore, Waddington et al. (1998), utilizing a simple hydrologic model (Roulet, 1991), predicted wetlands with mean water table positions within ± 0.1 m of the surface to experience enhanced CO₂ uptake under 2xCO₂ climate scenarios. Carroll and Crill (1997) predicted net-CO₂ release from peatland ecosystems in a warmer and drier climate using data collected from a New Hampshire wetland. Grogan et al. (2001) suggest changes in mid-winter temperatures in the Arctic will have profound impacts on carbon cycling.
1.3 Eddy Covariance

The eddy covariance (EC) technique is the most robust, direct, and defensible method of obtaining ecosystem-level CO₂ exchange (Baldocchi et al., 1988, 2001, 2003; Moncrieff et al., 1997). In Northern Canada, there have been very few multi-year subarctic/arctic wetland tundra EC, CO₂ exchange studies. Existing studies have have been undertaken at the Churchill Fen (Griffis et al., 2000; Lafleur et al., 2001) and at Daring Lake, NWT (Lafleur and Humphreys, 2007). In general, few comprehensive CO₂ exchange studies exist that assess controls on NEE. Additional comprehensive CO₂ exchange studies are needed in high latitude regions to more accurately quantify the exchange of CO₂ between these ecosystems and the atmosphere to assist modeling efforts in predicting the effects of climate change (McGuire et al., 2000, 2002).
1.4 Objectives

In this study I summarize carbon cycle research utilizing the eddy covariance technique over two consecutive growing seasons (2007 and 2008) from a subarctic wetland tundra sedge fen in the Hudson Bay Lowland (HBL). The objectives of this study were to (1) determine the growing season CO2 balance of the fen, (2) explore linkages between the intraannual variations of CO2 fluxes and environmental controls, and (3) compare results with those from previous years at this site and from similar sites elsewhere.
SECTION 2: SITE DESCRIPTION AND DATA COLLECTION

2.1 Site Description

This study was conducted at a wetland tundra sedge fen near Churchill, Manitoba, Canada (58°40’ N, 93° 50’ W). The research site is located approximately 18 km southeast of the Churchill Airport (58°44’ N, 94°03’ W) and 12.5 km south of the Hudson Bay shoreline (Fig. 1). Hudson Bay exerts a strong influence on the regional climate during the growing season (Rouse and Bello, 1985; Rouse, 1991). Patches of open woodland within close proximity of the site mark the edge of the northern boreal treeline. Continuous permafrost begins to the south of the site. The fen is extensive and its surface is relatively homogenous. Highly porous organic (peat) soil, 0.20-0.40 m deep, overlies glaciomarine till, consisting of silty-clay mineral soil. Its topography consists of small hummocks (47%), hollows (48%), and large hummocks (5%) (Griffis and Rouse, 2000). The site is 22 m above sea level, and vegetation and peat development at the site is estimated to have initiated about 2200 years ago assuming a constant rate of isostatic rebound (0.01 m y⁻¹).
Vascular species (Carex aquatilis, C. liminosa, C. saxatilis, C. gynocrates, Calamagrostis spp., Eriophorum spp., Arctagrostis latifolia, Juncus spp., and Equisetum variegatum) dominate the small hummocks (sedge lawns) which cover approximately 55% of the fen. There is an understory of Pseudocalliergon turgescens throughout most of the fen landscape. Large hummocks support a variety of vascular species (Betula glandulosa, Ledum palustre, Andromeda polifolia, Rhododendron lapponicum, R. subarcticum, Vaccinium vitis-idaea, V. uliginosum, Salix arctophila, and Carex spp.) and nonvascular species of lichen (Cladina stellaris, Cladonia. rangiferina) and moss (Dicranum undulatum). The hollows are dominated by P. turgescens.
2.2 Data Collection

Carbon dioxide and energy flux measurements were made during the growing seasons of 2007 (DOY 157-254) and 2008 (DOY 157-268). A tower-based EC system was used to obtain surface fluxes of momentum, CO₂, heat, and water vapour. Wind speed and virtual sonic temperature were measured at 20 Hz using a three-dimensional ultrasonic anemometer (CSAT3, Campbell Scientific®, Logan, Utah, USA). Water vapour and CO₂ molar density (mmol m⁻³) were measured at the same frequency using an open-path infrared gas analyzer (LI-7500, LICOR®, Lincoln, Nebraska, USA). The open-path infrared gas analyzer (IRGA) was calibrated on a monthly basis. Both the ultrasonic anemometer (CSAT) and IRGA were installed at a height of 3.9 m above the fen’s surface and separated by 20 cm with the CSAT oriented due north. Raw data were recorded on a micrologger (CR5000, Campbell Scientific®, Logan, Utah, USA), and transferred to a personal computer at 15 minute intervals via radio frequency (900 MHz) telemetry (Xtend-PKG© modem, MaxStream®, Minnetonka, Minnesota, USA). Covariances were calculated over 60 min intervals following standard procedures (Massman and Lee, 2002). Linear de-trending was used in the flux calculations of heat, water vapour, and CO₂ (Gash and Culf, 1996). Wind data from the sonic anemometer were rotated to force the mean crosswind and vertical wind speeds to zero and to align the streamwise wind with the mean wind vector (McMillan, 1988; Finnigan, 2003, 2004). High frequency attenuation of the cospectra due to the effects of sensor separation and path-length averaging were corrected using the transfer function method (Moore, 1986). Fluxes were calculated using corrected covariances taking into account air density
fluctuations (Webb et al., 1980). No correction was applied for instrument surface heating of the IRGA (Burba et al., 2008).

Air temperature (T\textsubscript{a}) and relative humidity (RH) were measured every 3 s at 1.8 m above the surface of the fen using a temperature and relative humidity probe (HMP45C, Vaisala\textsuperscript{©}, Helsinki, Finland) and saved on the data logger as half-hourly averages. Wind speed and direction were measured at 4.1 m. Small data gaps in T\textsubscript{a} and RH were filled using linear interpolation and larger gaps filled with data from the Churchill airport.

Upwelling and downwelling shortwave and longwave radiation were independently measured using pyranometers (PSP, Eppley\textsuperscript{©}, Newport, Rhode Island, USA) and pyrgeometers (PIR, Eppley\textsuperscript{©}, Newport, Rhode Island, USA) at a height of 1 m above the surface. Net radiation (Q\textsuperscript{*}) was measured using a pyrradiometer (Q7.1, REBS\textsuperscript{©}, Seattle, Washington, USA) and photosynthetic photon flux (PPFD) was measured using a quantum sensor (PAR LITE, Kipp and Zonen\textsuperscript{©}, Delft, The Netherlands) both mounted adjacent to the pyranometers and pyrgeometers.

Soil temperatures (T\textsubscript{s}) were measured using thermocouples (24 AWG Type-T) imbedded in wooden dowels at 10 cm intervals to a depth of 60 cm. A three junction averaging thermocouple was placed at a depth of 0.05 m with ends under three surface types (hummock, hollow, and sedge lawn). Three soil heat flux plates (CN3, Middleton\textsuperscript{©}, Melbourne, Australia) were placed at a depth of 0.10 m under the same aforementioned surface types. An average ground heat flux (Q\textsubscript{G}) was calculated accounting for storage
above the soil heat flux plates (Halliwel and Rouse, 1987). Soil measurements were made every 3s and stored as 30 minute averages on a micrologger (CR23x, Campbell Scientific®, Logan, Utah, USA). Water table measurements were taken every 1-7 days with rulers at four proximate locations around the tower.
2.3 Quality Control and Gap Filling

The EC data sets were filtered for erroneous values associated with instrument malfunction and adverse weather conditions. Values were removed when the optical path of the IRGA was obstructed, commonly during rain events, indicated by its diagnostic value. Nighttime (PPFD < 25 µmol m⁻² s⁻¹) flux values were removed during periods of insufficient turbulence (Fig. 2 and 3; friction velocity (u* ) < 0.25 m s⁻¹). In 2007 and 2008, 33% and 45% of the hourly EC fluxes were discarded, respectively.

Missing hourly flux values of NEE, latent heat (Qₑ), and sensible heat (Qₜ) were filled via linear interpolation and empirical models. Interpolation was used for NEE, Qₑ, and Qₜ gaps of 1-2 hours. Latent heat flux (Qₑ) and Qₜ gaps greater than 2 hours were filled using a linear relationship with Q* and Tₚ. Gaps in net ecosystem CO₂ exchange greater than 2 hours were filled using a rectangular hyperbolic relationship to describe gross ecosystem productivity (GEP) as a function of PPFD (eq. 1) and the standard Q₁₀ exponential relationship to describe ER as a function of Tₛ (eq. 2).

\[
\text{GEP} = \frac{\alpha \times \text{PPFD} \times \text{GEP}_\text{max}}{\alpha \times \text{PPFD} + \text{GEP}_\text{max}} \quad \text{(eq. 1)}
\]

\[
\text{ER} = R_{10} \times \frac{T_{\text{a}10}^{-10}}{10} \quad \text{(eq. 2)}
\]
Figure 2. Nocturnal (PPFD < 25 µmol photons m\(^{-2}\) s\(^{-1}\)) hourly (n = 530) net ecosystem CO\(_2\) exchange (µmol CO\(_2\) m\(^{-2}\) s\(^{-1}\)) as a function of friction velocity (\(u^*\); m s\(^{-1}\)) during the 2007 study period.

Figure 3. Nocturnal (PPFD < 25 µmol photons m\(^{-2}\) s\(^{-1}\)) hourly (n = 665) net ecosystem CO\(_2\) exchange (µmol CO\(_2\) m\(^{-2}\) s\(^{-1}\)) as a function of friction velocity (\(u^*\); m s\(^{-1}\)) during the 2008 study period.
The parameter $GEP_{\text{max}}$ is the photosynthetic capacity for unlimited PPFD and $\alpha$ is the apparent light-use efficiency. The parameter $R_{10}$ is the ecosystem respiration (ER) at the reference temperature ($10^\circ\text{C}$) and $Q_{10}$ is the relative increase in ER at a temperature $10^\circ\text{C}$ greater than the reference temperature (i.e. $20^\circ\text{C}$). The peat temperature ($T_s$) at a depth of 5 cm is shown in Fig. 4 and 5. Nighttime NEE measurements with sufficient turbulence were used to determine the relationship between ER and $T_s$. Gross ecosystem productivity (GEP) values were calculated as the difference between modelled ER and measured NEE.
Figure 4. Daily minimum and maximum average hourly soil temperature (°C) 5 cm below surface of the fen during 2007 study period.

Figure 5. Daily minimum and maximum average hourly soil temperature (°C) 5 cm below surface of the fen during 2008 study period.
2.4 Validation of Eddy Covariance Measurements

Validation of the EC system was determined by comparing available energy ($Q^*-Q_G$) to the sum of the measured latent and sensible heat fluxes ($Q_H+Q_E$), commonly referred to as energy balance closure (EBC). Hourly values of ($Q_H+Q_E$) were plotted against ($Q^*-Q_G$) and forced through zero obtaining slope values of 0.79 ($r^2 = 0.89$, $n = 1473$) and 0.82 ($r^2 = 0.85$, $n = 2065$) for 2007 and 2008, respectively (Fig. 6 and 7). Most results from available literature on EBC indicate that the difference between $Q^*$ and $Q_G$ to be greater than the sum of $Q_H$ and $Q_E$ indicating a lack of closure (Twine et al., 2000). Twine et al. (2000) studied the lack of closure from 4 different EC systems over the same grassland and found that the EC systems under-measured $Q_H$ and $Q_E$ fluxes systematically by 10-30%. Wilson et al. (2002) evaluated EBC at 22 FLUXNET sites comprising 50 site-years and found a general lack of closure. Energy balance closure (EBC) calculations from this site during both growing seasons indicate that the Churchill fen EC system under-measured $Q_H$ and $Q_E$ fluxes by approximately 20%.
Figure 6. Energy balance closure during the 2007 study period. Hourly values of sensible ($Q_H$) plus latent ($Q_E$) flux (W m$^{-2}$) vs. net radiation ($Q^*$) minus ground heat ($Q_G$) flux (W m$^{-2}$). Regression line is forced through origin (slope = 0.79, $r^2 = 0.89$, n = 1473).

Figure 7. Energy balance closure during the 2008 study period. Hourly values of sensible ($Q_H$) plus latent ($Q_E$) flux (W m$^{-2}$) vs. net radiation ($Q^*$) minus ground heat ($Q_G$) flux (W m$^{-2}$). Regression line is forced through origin (slope = 0.82, $r^2 = 0.85$, n = 2065).
2.5 Uncertainty in NEE Measurements

The uncertainty in EC measurement was categorized as either random or systematic (Goulden et al., 1996; Moncrieff et al., 1996; Baldocchi 2003). Random error was estimated by comparing EC measurements of NEE with modelled values using the rectangular hyperbolic and $Q_{10}$ relationships (Aurela et al., 2002; Fig. 8 and 9). Sources of systematic error are associated with the spectral correction routine and $u^*$ threshold data screening procedure. Systematic error within the data screening procedure was estimated by determining the relative difference in the growing season carbon budget with varying $u^*$ thresholds (Aurela et al., 2002; Hollinger and Richardson, 2005). Error within the spectral correction was estimated to be approximately 30%, combined with the average correction of about 30%, results in an error of approximately 9%. Total accuracy of the growing season CO$_2$ budget was taken as the root-sum-square of the random and systematic errors.
Figure 8. Modelled hourly NEE (µmol CO₂ m⁻² s⁻¹) vs. measured hourly NEE (µmol CO₂ m⁻² s⁻¹) during the 2007 study period (n = 884). Hourly NEE was modelled using Eq. (1) and Eq. (2) and calculated as NEE = GEP – ER. Parameter estimates (± S.E.) from regression line forced through origin are slope = 0.97 (± 0.01) and r² = 0.86.

Figure 9. Modelled hourly NEE (µmol CO₂ m⁻² s⁻¹) vs. measured hourly NEE (µmol CO₂ m⁻² s⁻¹) during the 2008 study period (n = 1232). Hourly NEE was modelled using Eq. (1) and Eq. (2) and calculated as NEE = GEP – ER. Parameter estimates (± S.E.) from regression line forced through origin are slope = 0.92 (± 0.01) and r² = 0.77.
SECTION 3: RESULTS

3.1 Environmental Conditions

3.1.1 General Environmental Conditions

Data from both measurement periods were grouped into four phenological periods based on previous published studies (e.g. Giffis and Rouse, 2001) and observations during both growing seasons: pre-green (DOY 157-170), early-green (DOY 171-205), late-green (DOY 206-240), and post-green (DOY 241-254). Data were also divided into two-week periods (2007: 7 two-week periods; 2008: 8 two-week periods). The research site received approximately 18 hours of sunlight on the summer solstice. At the end of the measurement period the site was receiving approximately 13 hours of sunlight.

Wind direction was categorized as either onshore or offshore as defined in Rouse and Bello (1985). Onshore winds dominated the pre- and early-green periods with approximately 60-70% of the all recorded winds blowing from the direction of the Hudson Bay in both years (Table 1). In 2007, the late- and post-green periods were characterized equally by onshore and offshore winds. In 2008, late-green period winds were the same as 2007 but post-green winds were almost 70% offshore. Table 2 and 3 summarize the wind regimes experienced during each two-week period with corresponding energy budget and environmental variables.
Average daily air temperature ($T_a$) was above normal (1971-2000 average) during all periods of both years except during the pre-green and post-green periods of 2007 (Table 1). In 2007, $T_a$ ranged from 0.5°C below (pre-green) to 1.3°C above (early-green) the 30-year mean. In 2008, $T_a$ was above normal in all periods ranging from 0.8°C (early-green) to 1.7°C (late-green) above the 30-year mean. Daily maximum air temperature exceeded 30°C during the summer of both measurement periods (Fig. 10). Most days during both measurement periods were above normal (1971-2000 average). Several days during each measurement period recorded minimum air temperatures greater than the normal temperature. Summertime (June, July, and August) $T_a$ was 11.1°C and 12.0°C in 2007 and 2008, respectively (Table 4). The start of the growing season was determined to be when $T_a > 5°C$ and the end of the growing season was determined to be when $T_a < 5°C$ for 7 consecutive days. Based on these criteria, the growing seasons were from DOY 183-259 (77 days) and DOY 175-265 (91 days) for 2007 and 2008, respectively. Air temperature was higher during all two-week periods in 2008 than 2007 except during the fourth (P4) two-week period (Table 2 and 3).

Measurements of PPFD and $Q^*$ were greater during the 2008 measurement period than during the 2007 measurement period (Table 1, 2, and 3). There was approximately 14% greater PPFD and 17% greater $Q^*$ in 2008 than in 2007. This increase in available energy during the 2008 measurement period resulted in 30% greater $Q_H$, 26% greater $Q_E$, and 51% greater $Q_G$ than during the 2007 measurement period.
Table 1. General environmental conditions during each phenological period during the 2007 and 2008 growing seasons

<table>
<thead>
<tr>
<th></th>
<th>2007</th>
<th></th>
<th>2008</th>
<th></th>
<th></th>
<th></th>
<th></th>
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<tbody>
<tr>
<td></td>
<td>On</td>
<td>Off</td>
<td>PPFD</td>
<td>Tamin</td>
<td>Tamax</td>
<td>Taavg</td>
<td>Ta_mean</td>
<td>Ts_min</td>
<td>Ts_max</td>
<td>VPD</td>
<td>P_tot</td>
<td>Et_tot</td>
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<tr>
<td>PRE</td>
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<td>481</td>
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<td>9.2</td>
<td>5.2</td>
<td>5.7</td>
<td>N/A</td>
<td>N/A</td>
<td>0.20</td>
<td>19.5</td>
<td>29.7</td>
<td>13.1</td>
<td></td>
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<tr>
<td>EARLY</td>
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<td>42</td>
<td>507</td>
<td>7.7</td>
<td>16.7</td>
<td>12.2</td>
<td>10.9</td>
<td>10.1</td>
<td>14.1</td>
<td>0.45</td>
<td>25.5</td>
<td>95.9</td>
<td>11.4</td>
<td></td>
</tr>
<tr>
<td>LATE</td>
<td>47</td>
<td>53</td>
<td>402</td>
<td>7.9</td>
<td>17.1</td>
<td>12.5</td>
<td>12.2</td>
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<td>14.4</td>
<td>0.41</td>
<td>48.5</td>
<td>73.3</td>
<td>2.4</td>
<td></td>
</tr>
<tr>
<td>POST</td>
<td>53</td>
<td>47</td>
<td>263</td>
<td>5.3</td>
<td>13.8</td>
<td>9.6</td>
<td>9.9</td>
<td>7.6</td>
<td>10.9</td>
<td>0.20</td>
<td>14</td>
<td>16.8</td>
<td>N/A</td>
<td></td>
</tr>
</tbody>
</table>

Hourly wind data were divided into onshore (On; %) and offshore (Off; %). PPFD (µmol m\(^{-2}\) s\(^{-1}\)) average photosynthetic photon flux density. Tamin, Tamax, and Taavg, (°C) are mean period minimum, maximum, and average air temperature, respectively, recorded at the research site. Ta\(_{\text{mean}}\) is 30-year mean (1971-2000) recorded at the Churchill airport. Ts_min and Ts_max (°C) are mean period maximum and minimum soil temperature (-0.05 m), respectively, recorded at the research site. VPD (kPa) is the mean daytime (PPFD > 25 µmol photons m\(^{-2}\) s\(^{-1}\)) vapour pressure deficit. P\(_{\text{tot}}\) (mm) is the total period precipitation recorded at the Churchill airport (58°44’ N, 94°03’ W). Et\(_{\text{tot}}\) (mm) is the total period evapotranspiration recorded at the research site. WT (cm) is the average height of the water table at the research site above the surface of the hollows. N/A is data not available.
Table 2: Wind regimes for each period of the 2007 study period with corresponding components of the energy balance and environmental variables.

<table>
<thead>
<tr>
<th>2007</th>
<th>On</th>
<th>Off</th>
<th>Q*</th>
<th>Q_H</th>
<th>Q_E</th>
<th>Q_G</th>
<th>EF</th>
<th>β</th>
<th>VPD</th>
<th>PPFD</th>
<th>T_a_max</th>
<th>T_a_min</th>
<th>T_s_max</th>
<th>T_s_min</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>65</td>
<td>35</td>
<td>170</td>
<td>49</td>
<td>76</td>
<td>N/A</td>
<td>0.61</td>
<td>0.64</td>
<td>0.25</td>
<td>582</td>
<td>9.2</td>
<td>1.3</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>P2</td>
<td>49</td>
<td>51</td>
<td>184</td>
<td>42</td>
<td>87</td>
<td>22</td>
<td>0.67</td>
<td>0.48</td>
<td>0.43</td>
<td>621</td>
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<td>38</td>
<td>99</td>
<td>16</td>
<td>0.72</td>
<td>0.38</td>
<td>0.44</td>
<td>609</td>
<td>14.8</td>
<td>7.5</td>
<td>14.5</td>
<td>10.4</td>
</tr>
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<td>64</td>
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<td>608</td>
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<td>16.4</td>
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</tr>
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<td>57</td>
<td>114</td>
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<td>0.45</td>
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<td>9.0</td>
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<td>17</td>
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<td>0.30</td>
<td>318</td>
<td>11.8</td>
<td>4.4</td>
<td>10.9</td>
<td>7.6</td>
</tr>
</tbody>
</table>

Hourly wind data were divided into onshore and offshore (%). Q* (MJ m^-2) is cumulative period net radiation. Q_H (MJ m^-2) is cumulative period sensible heat flux. Q_E (MJ m^-2) is cumulative period latent heat flux. Q_G (MJ m^-2) is cumulative period ground heat flux. Non-radiative (radiative) fluxes directed away from surface are positive (negative). EF (unitless) is the evaporative fraction (Q_E / (Q_H + Q_E)). β (unitless) is the Bowen ratio (Q_H / Q_E). VPD (kPa) is the mean daytime (PPFD > 25 µmol photons m^-2 s^-1) vapour pressure deficit. PPFD (mol m^-2) is the cumulative period photosynthetic photon flux density. T_a max and T_a min (°C) are mean period maximum and minimum air temperature, respectively. T_s min and T_s max (°C) are mean period maximum and minimum soil temperature (-0.05 m), respectively. N/A is data not available.

Table 3: Wind regimes for each period of the 2008 study period with corresponding components of the energy balance and environmental variables.

<table>
<thead>
<tr>
<th>2008</th>
<th>On</th>
<th>Off</th>
<th>Q*</th>
<th>Q_H</th>
<th>Q_E</th>
<th>Q_G</th>
<th>EF</th>
<th>β</th>
<th>VPD</th>
<th>PPFD</th>
<th>T_a_max</th>
<th>T_a_min</th>
<th>T_s_max</th>
<th>T_s_min</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>47</td>
<td>53</td>
<td>218</td>
<td>48</td>
<td>109</td>
<td>33</td>
<td>0.69</td>
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<td>0.45</td>
<td>708</td>
<td>12.0</td>
<td>1.3</td>
<td>8.9</td>
<td>3.6</td>
</tr>
<tr>
<td>P2</td>
<td>44</td>
<td>56</td>
<td>239</td>
<td>71</td>
<td>123</td>
<td>25</td>
<td>0.63</td>
<td>0.58</td>
<td>0.36</td>
<td>762</td>
<td>14.2</td>
<td>3.5</td>
<td>13.0</td>
<td>7.9</td>
</tr>
<tr>
<td>P3</td>
<td>50</td>
<td>50</td>
<td>213</td>
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<td>126</td>
<td>24</td>
<td>0.70</td>
<td>0.44</td>
<td>0.54</td>
<td>727</td>
<td>17.0</td>
<td>6.1</td>
<td>14.4</td>
<td>9.1</td>
</tr>
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<td>178</td>
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<td>100</td>
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<td>0.77</td>
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<td>20.9</td>
<td>8.7</td>
<td>15.6</td>
<td>10.8</td>
</tr>
<tr>
<td>P5</td>
<td>29</td>
<td>71</td>
<td>157</td>
<td>29</td>
<td>95</td>
<td>21</td>
<td>0.77</td>
<td>0.31</td>
<td>0.72</td>
<td>536</td>
<td>20.4</td>
<td>9.5</td>
<td>15.4</td>
<td>11.0</td>
</tr>
<tr>
<td>P6</td>
<td>48</td>
<td>52</td>
<td>112</td>
<td>13</td>
<td>80</td>
<td>13</td>
<td>0.86</td>
<td>0.16</td>
<td>0.65</td>
<td>408</td>
<td>18.8</td>
<td>8.5</td>
<td>14.3</td>
<td>10.1</td>
</tr>
<tr>
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<td>37</td>
<td>63</td>
<td>99</td>
<td>24</td>
<td>73</td>
<td>5</td>
<td>0.75</td>
<td>0.33</td>
<td>0.44</td>
<td>404</td>
<td>13.3</td>
<td>4.5</td>
<td>11.4</td>
<td>7.8</td>
</tr>
</tbody>
</table>

Hourly wind data were divided into onshore and offshore (%). Q* (MJ m^-2) is cumulative period net radiation. Q_H (MJ m^-2) is cumulative period sensible heat flux. Q_E (MJ m^-2) is cumulative period latent heat flux. Q_G (MJ m^-2) is cumulative period ground heat flux. Non-radiative (radiative) fluxes directed away from surface are positive (negative). EF (unitless) is the evaporative fraction (Q_E / (Q_H + Q_E)). β (unitless) is the Bowen ratio (Q_H / Q_E). VPD (kPa) is the mean daytime (PPFD > 25 µmol photons m^-2 s^-1) vapour pressure deficit. PPFD (mol m^-2) is the cumulative period photosynthetic photon flux density. T_a max and T_a min (°C) are mean period maximum and minimum air temperature, respectively. T_s min and T_s max (°C) are mean period maximum and minimum soil temperature (-0.05 m), respectively. N/A is data not available.
Figure 10. Daily maximum and minimum air temperatures recorded at the research site during the 2007 (a) and 2008 (b) growing seasons. The solid line represents the 30-year mean (1971-2000) daily air temperature recorded at the Churchill airport (58°44’ N, 94°03’ W).
Table 4: Comparison of mean daily air temperature (°C) during the 2007 and 2008 growing seasons.

<table>
<thead>
<tr>
<th></th>
<th>2007</th>
<th>2008</th>
<th>30-year mean (± S.D.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>May</td>
<td>1.7</td>
<td>-0.5</td>
<td>-0.7 (± 2.4)</td>
</tr>
<tr>
<td>June</td>
<td>5.9</td>
<td>7.8</td>
<td>6.6 (± 2.1)</td>
</tr>
<tr>
<td>July</td>
<td>15.4</td>
<td>13.5</td>
<td>12.0 (± 1.7)</td>
</tr>
<tr>
<td>August</td>
<td>12.0</td>
<td>14.7</td>
<td>11.7 (± 1.5)</td>
</tr>
<tr>
<td>September</td>
<td>5.4</td>
<td>5.7</td>
<td>5.6 (± 1.8)</td>
</tr>
</tbody>
</table>


Peat temperatures (T_s) 5 cm below the surface were higher during most periods during the 2008 measurement period compared to the 2007 measurement period (Table 1, 2 and 3). Peat temperatures further below the surface (-0.10, -0.20, and -0.30 m) were also higher during most periods of the 2008 measurement period compared to the 2007 measurement period (Table 5).

Table 5: Mean period peat temperatures during the 2007 and 2008 study periods.

<table>
<thead>
<tr>
<th></th>
<th>-0.10 m</th>
<th>-0.20 m</th>
<th>-0.30 m</th>
</tr>
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<tbody>
<tr>
<td>P1</td>
<td>N/A</td>
<td>0.8 (0.2)</td>
<td>N/A</td>
</tr>
<tr>
<td>P2</td>
<td>6.3 (2.7)</td>
<td>5.1 (0.4)</td>
<td>2.7 (1.4)</td>
</tr>
<tr>
<td>P3</td>
<td>9.4 (2.0)</td>
<td>11.2 (0.6)</td>
<td>5.6 (1.7)</td>
</tr>
<tr>
<td>P4</td>
<td>13.2 (1.1)</td>
<td>15.2 (0.6)</td>
<td>8.9 (1.1)</td>
</tr>
<tr>
<td>P5</td>
<td>10.1 (0.8)</td>
<td>15.1 (0.8)</td>
<td>7.6 (0.6)</td>
</tr>
<tr>
<td>P6</td>
<td>9.3 (1.4)</td>
<td>12.1 (1.2)</td>
<td>7.4 (0.8)</td>
</tr>
<tr>
<td>P7</td>
<td>8.4 (0.9)</td>
<td>7.6 (0.4)</td>
<td>6.8 (0.6)</td>
</tr>
<tr>
<td>P8</td>
<td>N/A</td>
<td>3.6 (0.4)</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Values represent the mean period peat temperature (°C) at depths of 10, 20, and 30 cm below the surface of the fen. Mean period peat temperature values were calculated by averaging the daily mean ((T_{s_{max}} + T_{s_{min}}) / 2) values within each period. Values in parentheses are standard error. N/A is data not available.
The 2008 measurement period was characterized by clearer skies and greater VPD (Fig. 12) compared to the 2007 measurement period (Fig. 11), suggesting that the 2008 measurement period was influenced by persistent high pressure to the south of the study site, advecting warm continental air into the region (Petrone and Rouse, 2000). In 2007, average period VPD ranged from 0.20 kPa (pre-green) to 0.45 kPa (early-green) (Table 1) and peaked in period four (P4) at 1.00 kPa (Table 2). In 2008, average period VPD ranged from 0.29 kPa (post-green) to 0.46 kPa (early-green) (Table 1) and peaked in period four (P4) at 0.77 kPa. Average VPD was 0.47 and 0.54 kPa in 2007 and 2008, respectively.
Figure 11. Daily daytime (PPFD > 25 µmol photons m⁻² s⁻¹) average vapour pressure deficit (kPa) during 2007 study period. VPD was calculated as the difference between the saturated vapour pressure (calculated using Clausius-Clapeyron equation) and actual vapour pressure (calculated using measured relative humidity).

Figure 12. Daily daytime (PPFD > 25 µmol photons m⁻² s⁻¹) average vapour pressure deficit (kPa) during 2008 study period. VPD was calculated as the difference between the saturated vapour pressure (calculated using Clausius-Clapeyron equation) and actual vapour pressure (calculated using measured relative humidity).
Table 6: Comparison of total precipitation (mm) during the 2007 and 2008 growing seasons.

<table>
<thead>
<tr>
<th></th>
<th>2007</th>
<th>2008</th>
<th>30-year mean (± S.D.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>May</td>
<td>26.0</td>
<td>48.5</td>
<td>31.9 (± 25.1)</td>
</tr>
<tr>
<td>June</td>
<td>28.5</td>
<td>100.0</td>
<td>44.3 (± 28.3)</td>
</tr>
<tr>
<td>July</td>
<td>28.5</td>
<td>20.1</td>
<td>56.0 (± 29.4)</td>
</tr>
<tr>
<td>August</td>
<td>44.5</td>
<td>147.5</td>
<td>68.3 (± 22.7)</td>
</tr>
<tr>
<td>September</td>
<td>87.5</td>
<td>26.7</td>
<td>63.4 (± 33.5)</td>
</tr>
</tbody>
</table>


Cold-season (Oct-May) precipitation (rainfall + water equivalent snowfall) amounts recorded at the Churchill airport (58°44’ N, 94°03’ W) were 152 mm in 2007 and 227.5 mm in 2008. Snowmelt had commenced and finished by the start of both measurement periods. Ruler measurements were compared with observations and photographs of the fen site and an arbitrary datum was determined relative to the mean surface of the hollows. In both years, early growing season water table heights (WT) were very high, particularly in 2007 with just the hummock tops above the WT (Fig. 13). Later in the seasons the WT gradually dropped, fluctuating with periodic precipitation events. Water table heights dropped 16 cm (2007) and 11 cm (2008) from early season highs. In 2008, initial WT was lower and dropped more rapidly early in the growing season than in 2007 (Fig. 14). Total precipitation amounts recorded at the Churchill airport (58°44’ N, 94°03’ W) during the measurement period were 107.5 mm in 2007 and 359.3 mm in 2008 (Table 1). Precipitation amounts peaked during the late-green period of both years and evapotranspiration peaked during the early-green period of both years (Table 1). In 2007, evapotranspiration (E_t) was greater than precipitation in every two-week period (Table 7). In 2008, there were three two-week periods where precipitation was greater than
evapotranspiration (Table 7). There were 66% more rain events during the 2008 measurement period compared to the 2007 measurement period (Table 7).
Figure 13. Total daily precipitation (mm) recorded at the Churchill airport (58°44’ N, 94°03’ W) and mean water table height (cm) above or below the surface of the hollows (0 cm = hollow surface) during the 2007 study period.

Figure 14. Total daily precipitation (mm) recorded at the Churchill airport (58°44’ N, 94°03’ W) and mean water table height (cm) above or below the surface of the hollows (0 cm = hollow surface) during the 2008 study period.
Table 7: Water budget during the 2007 and 2008 study periods.

<table>
<thead>
<tr>
<th></th>
<th>2007</th>
<th></th>
<th>2008</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>P</td>
<td>E</td>
<td>P – E</td>
<td>WT</td>
</tr>
<tr>
<td>P1</td>
<td>19.5</td>
<td>29.7</td>
<td>-1.0</td>
<td>13.1</td>
</tr>
<tr>
<td>P2</td>
<td>9.0</td>
<td>33.2</td>
<td>-2.4</td>
<td>13.8</td>
</tr>
<tr>
<td>P3</td>
<td>15.5</td>
<td>39.4</td>
<td>-2.4</td>
<td>10.9</td>
</tr>
<tr>
<td>P4</td>
<td>12.5</td>
<td>44.5</td>
<td>-3.2</td>
<td>5.2</td>
</tr>
<tr>
<td>P5</td>
<td>18.5</td>
<td>28.5</td>
<td>-1.0</td>
<td>1.9</td>
</tr>
<tr>
<td>P6</td>
<td>18.5</td>
<td>23.6</td>
<td>-0.5</td>
<td>N/A</td>
</tr>
<tr>
<td>P7</td>
<td>7.5</td>
<td>16.8</td>
<td>-0.9</td>
<td>N/A</td>
</tr>
<tr>
<td>P8</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

P is total period precipitation (mm). Values in parenthesis are days within period with recorded precipitation. Precipitation data was taken from Churchill, Manitoba airport (58°44’ N, 94°03’ W). E is total period evapotranspiration (mm). P – E is the difference between total period precipitation and total period evapotranspiration (cm). WT is mean period water table height above or below the surface of the hollows (0 cm = hollow surface).

Leaf-area index (LAI) was not measured during the 2007 and 2008 measurement periods. However, Raddatz et al. (2008) developed a relationship between the LAI and the base 5°C \((T_{\text{base}})\) accumulated growing-degree days (\(\Sigma \text{GDD}\)) from May 1\(^{\text{st}}\) using data collected from previous years at this site (Wessel and Rouse, 1994; Griffis and Rouse, 2001). Based on this relationship, the rapid foliage expansion period was from DOY 195-209 and DOY 197-216 in 2007 and 2008, respectively. Cumulative growing-degree days were greater in 2008 compared to 2007 except during the fourth (P4) and fifth (P5) two-week periods (Figure 15).
Figure 15. Cumulative growing degree-days ($T_{\text{base}} = 5^\circ\text{C}$) during the 2007 and 2008 growing seasons.
3.1.2 Diurnal Variation of Environmental Conditions

In both 2007 and 2008, hourly average PPFD peaks around solar noon during the early-green period at about 1325 and 1575 mol photons m\(^{-2}\) s\(^{-1}\), respectively (Fig. 16). Average hourly PPFD was consistently greater in 2008 than in 2007 except during the late-green period when they were equivalent. In 2007, T\(_a\) peaks during the early-afternoon hours of the early-green period and holds throughout the late-green period at about 16°C (Fig. 16). In 2008, T\(_a\) peaks during the early-afternoon hours of the late-green period at about 18°C. Average hourly T\(_a\) was consistently higher during 2008 except during the early and late hours of the early-green period. In 2007, VPD peaked in the afternoon hours at 0.76-0.81 kPa during the green periods and at 0.36-0.43 kPa during the pre- and late-green periods. In 2008, VPD peaked in the afternoon hours at 0.85-0.88 kPa during the green periods and at 0.61-0.66 kPa during the pre- and late-green periods (Fig. 16). Average hourly VPD is consistently greater during 2008 except during the early hours of the early-green period and the early-evening hours of the late-green period. Average hourly E\(_t\) peaked between or during the hours of peak PPFD and VPD (Fig. 16). In 2007 and 2008, peak E\(_t\) was greatest during the early-green period (0.30 and 0.39 mm hr\(^{-1}\), respectively) and lowest during the late-green period (0.14 and 0.23 mm hr\(^{-1}\), respectively). Average hourly E\(_t\) was consistently higher during 2008 except during late-green period when they were equivalent.
Figure 16. Average hourly PPFD (µmol m\(^{-2}\) s\(^{-1}\)), Ta (ºC), VPD (kPa), and \(E_t\) (mm hr\(^{-1}\)) during each phenological period (a: pre-green; b: early-green; c: late-green; d: post-green) during the 2007 and 2008 growing season period.
3.2 CO₂ Exchange

3.2.1 Daily and Two-Week Period CO₂ Exchange

Mean daily NEE was consistently greater during the 2008 measurement period compared to the 2007 measurement period (Fig. 17 and 18). In 2008, mean daily NEE peaked very early in the growing season during the third two-week period (P3) on DOY 190 at approximately 3.5 µmol CO₂ m⁻² s⁻¹ (Fig. 17). Mean daily NEE was near zero during the first two-week period (P1) of the 2008 measurement period (Fig. 17). Mean daily NEE returned to near-zero values later in the growing season during the start of the eighth two-week period (P8) of 2008 (Fig. 17). In 2007, mean daily NEE peaked later in the growing season compared to 2008 during the fifth two-week period (P5) on DOY 217 at approximately 2.5 µmol CO₂ m⁻² s⁻¹ (Fig. 18). Mean daily NEE was near zero during the first two two-week periods (P1 and P2) of the 2007 measurement period (Fig. 18). Mean daily NEE returned to near-zero values later in the growing season during the end of the seventh two-week period (P7) of 2007 (Fig. 17).

Mean two-week period NEE was consistently greater during the 2008 measurement compared to the 2007 measurement except during the sixth two-week period (P6) when they were similar (Fig 19). Mean period NEE peaked at approximately 2.5 µmol CO₂ m⁻² s⁻¹ in 2008 during the third two-week period (P3) and 1.5 µmol CO₂ m⁻² s⁻¹ during the fifth two-week period (P5) in 2007 (Fig. 19). Mean period NEE was negative (indicating CO₂ uptake) during all periods except the last two-week period of 2008 (P8) (Fig. 19).
Substantial net-CO$_2$ uptake was observed in both years, however higher daily, period, and cumulative net-CO$_2$ uptake was observed in 2008 measurement period compared to the 2007 measurement period (Fig. 17, 18, 19, and 20). Peak daily NEE occurred earlier in 2008 than 2007 (Fig. 17 and 18). Daily NEE increased more rapidly during the early-green period in 2008 illustrated by the diverging plots of cumulative daily NEE between years (Fig. 20). Daily NEE would diminish in late-August and become slightly positive in September indicating senescence and the end of the growing season (Fig. 20).
Figure 17. Mean daily NEE (µmol CO$_2$ m$^{-2}$ s$^{-1}$) during 2008 growing season. Values represent daily average net ecosystem CO$_2$ exchange and error bars represent ± 1 standard error (S.E.).

Figure 18. Mean daily NEE (µmol CO$_2$ m$^{-2}$ s$^{-1}$) during 2007 growing season. Values represent daily average net ecosystem CO$_2$ exchange and error bars represent ± 1 standard error (S.E.).
Figure 19. Mean NEE (µmol CO₂ m⁻² s⁻¹) during each 2-week period of the 2007 and 2008 study periods. Error bars represent ± 1 standard error (S.E.).

Figure 20. Cumulative daily NEE (g CO₂ m⁻²) during the study periods of 2007 (DOY: 154-255) and 2008 (DOY: 154-268). During the study periods of 2007 and 2008, the fen was a sink for CO₂ of -343 and -438 g CO₂ m⁻², respectively.
All phenological periods experienced greater mean GEP, ER, and NEE in 2008 compared to 2007 except during the pre-green period (Table 8). In 2007, average GEP, ER, and NEE peaked at -2.75, 1.62, and -1.25 µmol CO₂ m⁻² s⁻¹, respectively (Table 8). In 2008, average GEP, ER, and NEE peaked at -3.32, 1.92, and -1.63 µmol CO₂ m⁻² s⁻¹, respectively (Table 8). In 2007 and 2008, cumulative growing season NEE was -343 (± 79) and -450 (± 87) g CO₂ m⁻² with mean daily NEE of -3.5 and -4.6 g CO₂ m⁻² d⁻¹, respectively; estimated cumulative growing season GEP was -826 (± 190) and -1020 (± 197) g CO₂ m⁻² with mean daily GEP of -8.4 and -10.4 g CO₂ m⁻² d⁻¹, respectively; estimated cumulative growing season ER was 510 (± 117) and 570 (± 109) g CO₂ m⁻² with mean daily ER of 5.2 and 5.8 g CO₂ m⁻² d⁻¹, respectively (Table 8). In 2008, cumulative GEP was 23% greater, cumulative ER was 12% greater, resulting in 31% greater cumulative NEE compared to 2007 (Table 8). The ratio of ER/GEP was slightly higher in 2007; ER/GEP was 0.62 and 0.56 in 2007 and 2008, respectively (Table 8). The ratio of NEE/GEP was slightly higher in 2008; NEE/GEP was 0.42 and 0.44 in 2007 and 2008, respectively (Table 8).
Table 8. Summary of GEP, ER, and NEE during each phenological period of the 2007 and 2008 growing periods.

<table>
<thead>
<tr>
<th>YEAR</th>
<th>PERIOD</th>
<th>GEP</th>
<th>ER</th>
<th>NEE</th>
<th>NEE/GEP</th>
<th>ER/GEP</th>
<th>ΣGDD</th>
<th>ΣNEE</th>
<th>ΣGEP</th>
<th>ΣER</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>PRE</td>
<td>-1.02</td>
<td>0.79</td>
<td>-0.31</td>
<td>31</td>
<td>77</td>
<td>22</td>
<td>-17</td>
<td>-54</td>
<td>42</td>
</tr>
<tr>
<td></td>
<td>EARLY</td>
<td>-2.48</td>
<td>1.62</td>
<td>-0.99</td>
<td>40</td>
<td>65</td>
<td>255</td>
<td>-132</td>
<td>-330</td>
<td>216</td>
</tr>
<tr>
<td></td>
<td>LATE</td>
<td>-2.75</td>
<td>1.53</td>
<td>-1.25</td>
<td>45</td>
<td>56</td>
<td>262</td>
<td>-166</td>
<td>-366</td>
<td>204</td>
</tr>
<tr>
<td></td>
<td>POST</td>
<td>-1.41</td>
<td>0.89</td>
<td>-0.53</td>
<td>37</td>
<td>64</td>
<td>49</td>
<td>-28</td>
<td>-75</td>
<td>48</td>
</tr>
<tr>
<td></td>
<td>PRE</td>
<td>-0.84</td>
<td>0.66</td>
<td>-0.17</td>
<td>20</td>
<td>78</td>
<td>36</td>
<td>-9</td>
<td>-45</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>EARLY</td>
<td>-3.26</td>
<td>1.65</td>
<td>-1.63</td>
<td>50</td>
<td>51</td>
<td>233</td>
<td>-216</td>
<td>-433</td>
<td>220</td>
</tr>
<tr>
<td></td>
<td>LATE</td>
<td>-3.32</td>
<td>1.92</td>
<td>-1.42</td>
<td>43</td>
<td>58</td>
<td>311</td>
<td>-189</td>
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<td>-0.66</td>
<td>35</td>
<td>59</td>
<td>55</td>
<td>-35</td>
<td>-100</td>
<td>59</td>
</tr>
</tbody>
</table>

Average GEP, ER, and NEE (µmol CO₂ m⁻² s⁻¹) during each phenological period. NEE/GEP and ER/GEP are ratios (%). ΣGDD is cumulative period growing degree-days. ΣNEE is cumulative period NEE (g CO₂ m⁻²). ΣGEP is cumulative period GEP (g CO₂ m⁻²). ΣER is cumulative period ER (g CO₂ m⁻²).
Total daily NEE approached -12.9 g CO$_2$ m$^{-2}$ d$^{-1}$ in 2008 (Fig. 24) during the early-green period, and -9.5 g CO$_2$ m$^{-2}$ d$^{-1}$ in 2007 (Fig. 22) during the late-green period. Total daily NEE was consistently negative during both the 2007 and 2008 measurement periods indicating daily CO$_2$ uptake during most days (Fig. 21 and 22). Total daily NEE peaked earlier during the 2008 measurement period than during the 2007 measurement period (Fig. 21 and 22). In 2007, variations in total daily NEE corresponded closely with variations in total daily PPFD and minimum $T_a$ but did not correspond very well with maximum $T_s$ (Fig. 21). Maximum daily peat temperature at a depth of 10 cm peaked near 8°C during the middle of the growing season in 2007 (Fig. 21). In 2008, variation in total daily NEE corresponded closely with variations in total daily PPFD, minimum $T_a$, and maximum $T_s$ (Fig. 22). Maximum daily peat temperature at a depth of 10 cm peaked around 14°C twice during the growing season of 2008 (Fig. 22). There was greater variation in $T_s$ during the 2008 measurement period than during the 2007 measurement period (Fig. 21 and 22).
Figure 21. Total daily net ecosystem CO₂ exchange (g CO₂ m⁻² d⁻¹) (bars) and minimum daily air temperature (°C) (top graph), total daily photosynthetic photon flux density (mol m⁻²) (middle graph), and maximum daily peat temperature at a depth of 10 cm (°C) (bottom graph) during the 2007 measurement period.
Figure 22. Total daily net ecosystem CO₂ exchange (g CO₂ m⁻² d⁻¹) (bars) and minimum daily air temperature (°C) (top graph), total daily photosynthetic photon flux density (mol m⁻²) (middle graph), and maximum daily peat temperature at a depth of 10 cm (°C) (bottom graph) during the 2008 measurement period.
3.2.2 Diurnal CO₂ Exchange

In both years, peak hourly average NEE tended to be during late morning or close to noon, corresponding to high hourly average GEP and lower hourly average ER (Fig. 23). Peak hourly average GEP occurred shortly after peak hourly average NEE corresponding with peak hourly average PPFD (Fig. 23). Peak hourly average ER occurred during late afternoon or early evening corresponding to peak hourly average Tₘ (Fig. 23). In 2008, hourly average GEP was greater in all periods except the pre-green period (Fig. 23). Hourly average ER was very similar during all periods except the late-green period when 2008 ER was consistently greater than 2007 ER (Fig. 23). In 2008, hourly average NEE was consistently greater during all periods except the pre-green period (Fig. 23). In general, the ecosystem was a net-CO₂ source during the hours of 2000-0600 CST and a net-CO₂ sink during the hours of 0600-2000 CST (Fig. 23).

Pre-green hourly average NEE was very similar in both years ranging from -1.18 to 0.76 µmol CO₂ m⁻² s⁻¹ with slightly greater hourly average GEP in 2007 peaking at -2.03 µmol CO₂ m⁻² s⁻¹ (Fig. 23). Early-green hourly average NEE indicated greater CO₂ uptake in 2008 with hourly average values peaking at -4.68 µmol CO₂ m⁻² s⁻¹ driven by greater hourly average GEP which peaked at -6.51 µmol CO₂ m⁻² s⁻¹ (Fig. 23). Late-green hourly average NEE was more similar between years but still indicated greater CO₂ uptake in 2008 (Fig. 23). Late-green hourly average ER was slightly greater in 2008 causing hourly average NEE to be more similar between years during the late-green period than during the early-green period (Fig. 23). Late-green hourly average NEE peaked at -5.39 µmol CO₂ m⁻² s⁻¹ again driven by greater hourly average GEP which
peaked at -7.49 µmol CO$_2$ m$^{-2}$ s$^{-1}$ (Fig. 23). Post-green hourly average NEE peaked at -3.97 µmol CO$_2$ m$^{-2}$ s$^{-1}$ in 2008 again driven by greater hourly average GEP which peaked at -4.91 µmol CO$_2$ m$^{-2}$ s$^{-1}$ (Fig. 23).
Figure 23. Average hourly ER (μmol CO$_2$ m$^{-2}$ s$^{-1}$), GEP (μmol CO$_2$ m$^{-2}$ s$^{-1}$), and NEE (μmol CO$_2$ m$^{-2}$ s$^{-1}$) during each phenological period (a: pre-green; b: early-green; c: late-green; d: post-green). ER values were calculated using the standard Q$_{10}$ relationship. GEP was calculated as the difference between measured NEE and modeled ER.
3.3 Modelling of GEP and ER

3.3.1 Modelling of Gross Ecosystem Productivity

Bin-averaged GEP values during each phenological period of both the 2007 and 2008 measurement periods fit the rectangular hyperbolic GEP-PPFD model well (Fig. 24, Table 9, and Table 10). The coefficients of determination ($r^2$) was very high during each phenological period of 2007 ($r^2 = 0.86-0.98$) and 2008 ($r^2 = 0.65-0.99$) (Table 9 and 10). During the late-green period of 2007, $\alpha$ and GEP$_{\text{max}}$ peaked at 15.00 mmol CO$_2$ mol$^{-1}$ PPFD and 10.93 µmol CO$_2$ m$^{-2}$ s$^{-1}$, respectively. During the late-green period of 2008, $\alpha$ and GEP$_{\text{max}}$ peaked at 22.76 mmol CO$_2$ mol$^{-1}$ PPFD and 11.36 µmol CO$_2$ m$^{-2}$ s$^{-1}$, respectively. Entire growing season $\alpha$ and GEP$_{\text{max}}$ values were 14.37 mmol CO$_2$ mol$^{-1}$ PPFD and 8.61 µmol CO$_2$ m$^{-2}$ s$^{-1}$, respectively in 2007 and 14.57 mmol CO$_2$ mol$^{-1}$ PPFD and 7.98 µmol CO$_2$ m$^{-2}$ s$^{-1}$, respectively in 2008.

Bin-averaged GEP values during each two-week period of both the 2007 and 2008 measurement periods also fit the rectangular hyperbolic GEP-PPFD model well (Table 11 and 12). The coefficient of determination ($r^2$) was very high during each two-week period of 2007 ($r^2 = 0.68-0.98$) and 2008 ($r^2 = 0.84-0.98$) (Table 11 and 12). In 2007, $\alpha$ and GEP$_{\text{max}}$ peaked during the fourth two-week period (P4) at 23.58 mmol CO$_2$ mol$^{-1}$ PPFD and 10.40 µmol CO$_2$ m$^{-2}$ s$^{-1}$, respectively (Table 11). In 2008, $\alpha$ peaked at 24.06 mmol CO$_2$ mol$^{-1}$ PPFD during the sixth two-week period (P6) and GEP$_{\text{max}}$ peaked at 11.23 µmol CO$_2$ m$^{-2}$ s$^{-1}$ during the fifth two-week period (P5) (Table 12).
Figure 24. Relationship between GEP (μmol CO₂ m⁻² s⁻¹) and PPFD (μmol photons m⁻² s⁻¹) during each phenological period (pre-green: DOY 157-170; early-green: DOY 171-205; late-green: DOY 206-240; post-green: DOY 241-254) of each growing season. GEP is measured on the vertical axis and PPFD is measured on the horizontal axis. Symbols represent bin-averaged 100 μmol photons m⁻² s⁻¹ PPFD values of hourly daytime (PPFD > 25 μmol photons m⁻² s⁻¹) GEP fluxes during times of sufficient turbulence (u* > 0.25). Hourly GEP values were calculated as the difference between measured NEE and modeled ER. Reference line represents rectangular hyperbolic model estimated via nonlinear least squares regression (Levenberg-Marquardt).
Table 9: Rectangular hyperbolic GEP model parameter values during each phenological period of the 2007 growing season.

<table>
<thead>
<tr>
<th>Period</th>
<th>$\alpha$ (mmol CO$_2$ mol$^{-1}$ photons)</th>
<th>$\text{GEP}_{\text{max}}$ (µmol CO$_2$ m$^{-2}$ s$^{-1}$)</th>
<th>$r^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-Green</td>
<td>4.27 (0.70)</td>
<td>3.66 (0.45)</td>
<td>0.88</td>
</tr>
<tr>
<td>Early-Green</td>
<td>14.69 (2.83)</td>
<td>6.73 (0.59)</td>
<td>0.86</td>
</tr>
<tr>
<td>Late-Green</td>
<td>15.00 (0.99)</td>
<td>10.93 (0.52)</td>
<td>0.98</td>
</tr>
<tr>
<td>Post-Green</td>
<td>9.87 (1.94)</td>
<td>7.41 (1.26)</td>
<td>0.89</td>
</tr>
<tr>
<td>Growing Season</td>
<td>14.37 (1.42)</td>
<td>8.61 (0.54)</td>
<td>0.91</td>
</tr>
</tbody>
</table>

Hourly GEP was calculated as the difference between measured daytime (PPFD > 25 µmol photons m$^{-2}$ s$^{-1}$) hourly NEE and modelled hourly ER. Estimated model parameter values for each phenological period were calculated via nonlinear least squares regression (Levenberg-Marquardt) of bin-averaged 100 µmol m$^{-2}$ s$^{-1}$ PPFD values of hourly GEP. $\alpha$ (mmol CO$_2$ mol$^{-1}$ photons) is the initial slope of the light curve at low PPFD or the apparent light-use efficiency. $\text{GEP}_{\text{max}}$ (µmol CO$_2$ m$^{-2}$ s$^{-1}$) is the maximum light-saturated photosynthetic capacity. Entire growing season parameter values were estimated using bin-averaged 50 µmol m$^{-2}$ s$^{-1}$ PPFD values of hourly GEP excluding PPFD values > 1625 µmol m$^{-2}$ s$^{-1}$. Values in parenthesis represent standard error.

Table 10: Rectangular hyperbolic GEP model parameter values during each phenological period of the 2008 growing season.

<table>
<thead>
<tr>
<th>Period</th>
<th>$\alpha$ (mmol CO$_2$ mol$^{-1}$ photons)</th>
<th>$\text{GEP}_{\text{max}}$ (µmol CO$_2$ m$^{-2}$ s$^{-1}$)</th>
<th>$r^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-Green</td>
<td>3.10 (0.97)</td>
<td>2.48 (0.54)</td>
<td>0.65</td>
</tr>
<tr>
<td>Early-Green</td>
<td>20.28 (2.59)</td>
<td>7.62 (0.38)</td>
<td>0.94</td>
</tr>
<tr>
<td>Late-Green</td>
<td>22.76 (1.46)</td>
<td>11.36 (0.39)</td>
<td>0.99</td>
</tr>
<tr>
<td>Post-Green</td>
<td>14.43 (1.94)</td>
<td>7.02 (0.57)</td>
<td>0.95</td>
</tr>
<tr>
<td>Growing Season</td>
<td>14.57 (1.09)</td>
<td>7.98 (0.35)</td>
<td>0.95</td>
</tr>
</tbody>
</table>

Hourly GEP was calculated as the difference between measured daytime (PPFD > 25 µmol photons m$^{-2}$ s$^{-1}$) hourly NEE and modelled hourly ER. Estimated model parameter values for each phenological period were calculated via nonlinear least squares regression (Levenberg-Marquardt) of bin-averaged 100 µmol m$^{-2}$ s$^{-1}$ PPFD values of hourly GEP. $\alpha$ (mmol CO$_2$ mol$^{-1}$ photons) is the initial slope of the light curve at low PPFD or the apparent light-use efficiency. $\text{GEP}_{\text{max}}$ (µmol CO$_2$ m$^{-2}$ s$^{-1}$) is the maximum light-saturated photosynthetic capacity. Entire growing season parameter values were estimated using bin-averaged 50 µmol m$^{-2}$ s$^{-1}$ PPFD values of hourly GEP excluding PPFD values > 1625 µmol m$^{-2}$ s$^{-1}$. Values in parenthesis represent standard error.
Table 11: Rectangular hyperbolic GEP-PPFD model parameter values during each 2-week period of the 2007 growing season.

<table>
<thead>
<tr>
<th>2007</th>
<th>α</th>
<th>GEP&lt;sub&gt;max&lt;/sub&gt;</th>
<th>r²</th>
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</thead>
<tbody>
<tr>
<td>P1</td>
<td>5.69 (1.36)</td>
<td>2.96 (0.36)</td>
<td>0.75</td>
</tr>
<tr>
<td>P2</td>
<td>11.58 (3.34)</td>
<td>4.21 (0.47)</td>
<td>0.68</td>
</tr>
<tr>
<td>P3</td>
<td>17.16 (1.87)</td>
<td>7.64 (0.38)</td>
<td>0.95</td>
</tr>
<tr>
<td>P4</td>
<td>23.58 (2.72)</td>
<td>10.40 (0.56)</td>
<td>0.95</td>
</tr>
<tr>
<td>P5</td>
<td>22.44 (3.06)</td>
<td>8.87 (0.54)</td>
<td>0.91</td>
</tr>
<tr>
<td>P6</td>
<td>13.42 (0.95)</td>
<td>10.01 (0.55)</td>
<td>0.98</td>
</tr>
<tr>
<td>P7</td>
<td>11.31 (2.51)</td>
<td>5.81 (0.87)</td>
<td>0.84</td>
</tr>
<tr>
<td>P1-P7</td>
<td>14.37 (1.42)</td>
<td>8.61 (0.54)</td>
<td>0.91</td>
</tr>
</tbody>
</table>

Hourly GEP was calculated as the difference between measured daytime (PPFD > 25 µmol photons m<sup>-2</sup> s<sup>-1</sup>) hourly NEE and modelled hourly ER. Estimated model parameter values were calculated via nonlinear least squares regression (Levenberg-Marquardt) of bin-averaged 50 µmol m<sup>-2</sup> s<sup>-1</sup> PPFD values of hourly GEP. α (mmol CO<sub>2</sub> mol<sup>-1</sup> photons) is the initial slope of the light curve at low PPFD or the apparent light-use efficiency. GEP<sub>max</sub> (µmol CO<sub>2</sub> m<sup>-2</sup> s<sup>-1</sup>) is the maximum light-saturated photosynthetic capacity. Entire growing season (P1-P7) parameter values were estimated excluding PPFD values > 1625 µmol m<sup>-2</sup> s<sup>-1</sup>. Values in parenthesis represent standard error.

Table 12: Rectangular hyperbolic GEP-PPFD model parameter values during each 2-week period of the 2008 growing season.

<table>
<thead>
<tr>
<th>2008</th>
<th>α</th>
<th>GEP&lt;sub&gt;max&lt;/sub&gt;</th>
<th>r²</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>4.75 (0.87)</td>
<td>3.39 (0.40)</td>
<td>0.84</td>
</tr>
<tr>
<td>P2</td>
<td>12.68 (2.14)</td>
<td>5.28 (0.38)</td>
<td>0.88</td>
</tr>
<tr>
<td>P3</td>
<td>15.62 (1.61)</td>
<td>10.37 (0.66)</td>
<td>0.95</td>
</tr>
<tr>
<td>P4</td>
<td>22.88 (3.30)</td>
<td>11.17 (0.81)</td>
<td>0.92</td>
</tr>
<tr>
<td>P5</td>
<td>23.28 (2.57)</td>
<td>11.23 (0.63)</td>
<td>0.95</td>
</tr>
<tr>
<td>P6</td>
<td>24.06 (3.10)</td>
<td>9.76 (0.63)</td>
<td>0.94</td>
</tr>
<tr>
<td>P7</td>
<td>14.88 (1.17)</td>
<td>7.55 (0.37)</td>
<td>0.98</td>
</tr>
<tr>
<td>P8</td>
<td>5.28 (0.97)</td>
<td>3.65 (0.67)</td>
<td>0.91</td>
</tr>
<tr>
<td>P1-P8</td>
<td>14.57 (1.09)</td>
<td>7.98 (0.35)</td>
<td>0.95</td>
</tr>
</tbody>
</table>

Hourly GEP was calculated as the difference between measured daytime (PPFD > 25 µmol photons m<sup>-2</sup> s<sup>-1</sup>) hourly NEE and modelled hourly ER. Estimated model parameter values were calculated via nonlinear least squares regression (Levenberg-Marquardt) of bin-averaged 50 µmol m<sup>-2</sup> s<sup>-1</sup> PPFD values of hourly GEP. α (mmol CO<sub>2</sub> mol<sup>-1</sup> photons) is the initial slope of the light curve at low PPFD or the apparent light-use efficiency. GEP<sub>max</sub> (µmol CO<sub>2</sub> m<sup>-2</sup> s<sup>-1</sup>) is the maximum light-saturated photosynthetic capacity. Entire growing season (P1-P8) parameter values were estimated excluding PPFD values > 1625 µmol m<sup>-2</sup> s<sup>-1</sup>. Values in parenthesis represent standard error.
3.3.2 Modelling of Ecosystem Respiration

Bin-averaged ER values during each measurement period fit the Q_{10} relationship (ER-T_s) well (Fig. 25 and Table 13). The coefficient of determination ($r^2$) was high during both the 2007 ($r^2 = 0.98$) and 2008 ($r^2 = 0.94$) measurement periods (Table 13). Parameter values for Q_{10} were estimated to be 3.9 and 4.7 and R_{10} were estimated to be 1.08 and 1.18 $\mu$mol CO$_2$ m$^{-2}$ s$^{-1}$ in 2007 and 2008, respectively (Table 13). The R_{10} parameter value represents the expected amount of ER at a temperature of 10°C. The Q_{10} parameter value represents the expected increase in ER given a 10°C increase in soil temperature with respect to R_{10}. A Q_{10} parameter value equal to 4.7 indicates that ER at T_s = 20°C is expected to be 4.7 times greater than ER at T_s = 10°C.
Figure 25. Relationship between ecosystem respiration (μmol CO$_2$ m$^{-2}$ s$^{-1}$) and soil temperature (-0.05 m) during the 2007 study period (DOY: 157-254; left graph) and the 2008 study period (DOY: 157-268; right graph). Circles represent bin-averaged 1°C soil temperature values of hourly nocturnal (PPFD < 25 μmol photons m$^{-2}$ s$^{-1}$) NEE fluxes (2007: n = 106; 2008: n = 234) during times of sufficient turbulence ($u^* > 0.25$). Error bars represent ± 1 S.E. The 2007 study period (left-graph) reference line represents exponential Q$_{10}$ model ($R_{10} = 1.08$ μmol CO$_2$ m$^{-2}$ s$^{-1}$, $Q_{10} = 3.88, r^2 = 0.98$) estimated via nonlinear least squares regression (Levenberg-Marquardt). The 2008 study period (right-graph) reference line represents exponential Q$_{10}$ model ($R_{10} = 1.18$ μmol CO$_2$ m$^{-2}$ s$^{-1}$, $Q_{10} = 4.72, r^2 = 0.94$) estimated via nonlinear least squares regression (Levenberg-Marquardt).

Table 13: Exponential Q$_{10}$ ER model parameter values for 2007 and 2008 growing seasons.

<table>
<thead>
<tr>
<th>Year</th>
<th>$Q_{10}$</th>
<th>$R_{10}$</th>
<th>$r^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2007</td>
<td>3.88 (0.31)</td>
<td>1.08 (0.04)</td>
<td>0.98</td>
</tr>
<tr>
<td>2008</td>
<td>4.72 (0.58)</td>
<td>1.18 (0.08)</td>
<td>0.94</td>
</tr>
</tbody>
</table>

Model parameters were estimated via nonlinear least squares regression (Levenberg-Marquardt) of bin-averaged 1°C soil temperature (-0.05 m) values of nocturnal (PPFD < 25 μmol m$^{-2}$ s$^{-1}$) hourly NEE values. $R_{10}$ (μmol CO$_2$ m$^{-2}$ s$^{-1}$) is ER at 10°C. The $Q_{10}$ temperature coefficient (unitless) represents the factor increase in ER at a temperature 10°C greater than the reference temperature (10°C). Values in parenthesis represent standard error.
3.4 Water Use Efficiency

In general, C3 plants lose 500 molecules of H₂O for every CO₂ molecule fixed by photosynthesis (Taiz and Zeiger, 2006). The reciprocal of this transpiration rate is referred to as the water use efficiency (WUE), 1/500, or 2 mmol CO₂ mol⁻¹ H₂O. Water use efficiency is a valuable ecophysiological parameter comparing plant carbon uptake to plant water conservation. Water use efficiency, GEP, and evapotranspiration (ET) were calculated for all hours with PPFD > 400 µmol m⁻² s⁻¹ and displayed as a 5-day running average throughout both growing seasons. Two particularly hot and dry periods during the 2008 growing season (DOY 200-204 and DOY 223-227) were analyzed in more detail (Fig. 26). Additionally, ET was compared to an equilibrium ET rate (ETₑ𝑞), more commonly known as the Priestley-Taylor evaporation coefficient (αₑ𝑞). A αₑ𝑞 value near 1.26 is indicative of a freely evaporating surface (Priestley and Taylor, 1972).
Figure 26. Two warm and dry periods (Period 1: DOY 200-204; Period 2: DOY 223-227) during the 2008 growing season. First row graphs (1a and 2a) are average hourly Ta (°C; left-axis; open-diamond) and average hourly PPFD (μmol photons m$^{-2}$ s$^{-1}$; right axis; open-triangle). Second row graphs (1b and 2b) are average hourly ER (μmol CO$_2$ m$^{-2}$ s$^{-1}$; open-triangle) and GEP (μmol CO$_2$ m$^{-2}$ s$^{-1}$; open-square). Third row graphs (1c and 2c) are average hourly WUE (mmol CO$_2$ mol$^{-1}$ H$_2$O; left-axis; open-triangle), average hourly VPD (kPa; left-axis; open-circle), average hourly $\alpha_{PT}$ (unitless; right-axis; open-square), and average hourly $E_t$ (mm hr$^{-1}$; right-axis; open-diamond).
A Priestley-Taylor evaporation coefficient less than unity ($\alpha_{PT} < 1$) indicates strong surface control over evaporation. In 2008, the five-day running mean of midday $\alpha_{PT}$ ranged from 0.77 to 1.15 and averaged 0.97 for the entire growing season. The five-day running mean of midday VPD ranged from 0.12 to 1.57 kPa and averaged 0.54 kPa for the entire growing season. During 2008, lower $\alpha_{PT}$ values corresponded to higher VPD values indicating stomatal control on evaporation at the leaf surface as atmospheric demand for water increases. In 2007, the five-day running mean of midday $\alpha_{PT}$ ranged from 0.65 to 1.02 and averaged 0.84 for the entire growing season. The five-day running mean of midday VPD ranged from 0.14 to 1.57 kPa and averaged 0.57 kPa for the entire growing season. Variation in $\alpha_{PT}$ did not correspond well with VPD during the 2007 growing season but $\alpha_{PT}$ values were consistently below unity evidencing surface control on ET.

In 2007, the 5-day running mean of midday WUE ranged from 0.55 to 2.70 mmol CO$_2$ mol$^{-1}$ H$_2$O and averaged 1.58 mmol CO$_2$ mol$^{-1}$ H$_2$O. The 5-day running mean of midday GEP ranged from -1.60 to -8.01 µmol CO$_2$ m$^{-2}$ s$^{-1}$ and averaged -4.50 µmol CO$_2$ m$^{-2}$ s$^{-1}$. The 5-day running mean of midday ET ranged from 1.7 to 4.6 mmol H$_2$O m$^{-2}$ s$^{-1}$ and averaged 2.9 mmol H$_2$O m$^{-2}$ s$^{-1}$. In 2008, the 5-day running mean of midday WUE ranged from 0.33 to 3.39 mmol CO$_2$ mol$^{-1}$ H$_2$O and averaged 1.63 mmol CO$_2$ mol$^{-1}$ H$_2$O. The 5-day running mean of midday GEP ranged from -1.20 to -8.10 µmol CO$_2$ m$^{-2}$ s$^{-1}$ and averaged -5.50 µmol CO$_2$ m$^{-2}$ s$^{-1}$. The 5-day running mean of midday ET ranged from 2.2 to 4.7 mmol H$_2$O m$^{-2}$ s$^{-1}$ and averaged 3.5 mmol H$_2$O m$^{-2}$ s$^{-1}$. Both GEP and ET were
greater in 2008 with a greater increase in GEP compared to ET evidenced by the greater WUE values in 2008 compared to 2007.

The hottest and driest periods of the two growing seasons occurred during 2008 (DOY 200-204 and DOY 223-227). Both of these 5-day periods occurred during the middle of the growing season characterized by maximum LAI and low WT depths. During the earlier of two 5-day periods (DOY 200-204), maximum average hourly $T_a$ was 25.0°C occurring between 1300-1400 CST, maximum average hourly PPFD was 1689 mol photons m$^{-2}$ s$^{-1}$ occurring between 1100-1200 CST, maximum average hourly ET was 0.35 mm hr$^{-1}$ occurring between 1200-1300 CST, maximum average hourly VPD was 1.84 kPa occurring between 1300-1400 CST, minimum average hourly $\alpha_{PT}$ was 0.62 occurring between 0700-0800 CST, maximum average hourly WUE was 4.15 mmol CO$_2$ mol$^{-1}$ H$_2$O occurring between 0600-0700 CST, and maximum average hourly GEP was -7.16 µmol CO$_2$ m$^{-2}$ s$^{-1}$ occurring between 0800-0900 CST. During the later of the two 5-day periods (DOY 223-227), maximum average hourly $T_a$ was 29.2°C occurring between 1400-1500 CST, maximum average hourly PPFD was 1462 mol photons m$^{-2}$ s$^{-1}$ occurring between 1300-1400 CST, maximum average hourly ET was 0.40 mm hr$^{-1}$ occurring between 1300-1400 CST, maximum average hourly VPD was 1.84 kPa occurring between 1400-1500 CST, minimum average hourly $\alpha_{PT}$ was 0.73 occurring between 0900-1000 CST, maximum average hourly WUE was 3.72 mmol CO$_2$ mol$^{-1}$ H$_2$O occurring between 0700-0800 CST, and maximum average hourly GEP was -8.99 µmol CO$_2$ m$^{-2}$ s$^{-1}$ occurring between 0800-0900 CST.
4.1 Environmental Controls on NEE

4.1.1 NEE and PPFD

High latitude tundra ecosystems are light-limited ecosystems (Tieszen et al., 1980). Daytime NEE is largely controlled by the PPFD incident on the ecosystem and most often a rectangular hyperbolic relationship best describes the NEE-PPFD relationship (Frolking et al., 1998). Rectangular hyperbolic parameter values differed greatly between the different phenological periods and between growing seasons over this fen. In 2008, light-use efficiency values (α) were much higher during all phenological periods except the pre-green period and maximum gross ecosystem productivity (GEP\textsubscript{max}) values were greater during the early- and late-green periods. These higher parameter values correspond to predominately higher average PPFD and T\textsubscript{a} during the 2008 growing season. The higher T\textsubscript{a} during 2008 led to an earlier start (1 week) and later end (1 week) to the growing season. An earlier start to the growing season can greatly increase early season CO\textsubscript{2} uptake given the higher PPFD amounts near the summer solstice. Maximum daily rates of NEE were occurring in early-July in 2008 while maximum daily rates of NEE were not occurring until early-August in 2007. Maximum NEE occurred on DOY 217 (-9.8 g CO\textsubscript{2} m\textsuperscript{-2} d\textsuperscript{-1}) in 2007 and on DOY 190 (-12.8 g CO\textsubscript{2} m\textsuperscript{-2} d\textsuperscript{-1}) in 2008. The increased length of the growing season in 2008 most likely contributed to earlier leaf emergence and enhanced productivity among vascular species, early growth and enhanced productivity among nonvascular species, and prolonged productivity late in
the growing season among all species. However, pre-green parameter values indicate a more productive ecosystem in 2007 which may have been due to the lower WT in early-2008 which would have led to water stress and the desiccation of the bryophyte/lichen communities given that mosses begin to assimilate CO$_2$ immediately following snowmelt (Oechel, 1976).
4.1.2 NEE and Temperature

Temperature is an important controlling factor on both GEP and ER. Dark reactions are highly impacted by temperature given the temperature dependent activity of the enzyme Rubisco. Evidence suggests arctic plants have broad and low temperature optima for photosynthesis (Oechel, 1976; Tieszen et al., 1980). However, the productivity of arctic plants is severely restricted by low temperatures and short growing season. The increase in CO₂ uptake measured in 2008 could be largely attributed to warmer June and August temperatures, causing an earlier start and later end to the growing season. Estimated cumulative GEP in 2007 was 826 g CO₂ m⁻² and 1041 g CO₂ m⁻² in 2008. Higher Tₐ quite often leads to higher atmospheric demand for water (VPD) which was observed in 2008 but WT levels were not low enough to impact productivity. Ecosystem respiration was largely controlled by Tₛ and an exponential relationship best describes the ER-Tₛ relationship. Parameter values for the exponential Q₁₀ relationship were greater in 2008 compared to 2007. In 2008, the Q₁₀ parameter was 4.72 indicating that ER would be 4.72 times greater at a soil temperature of 20°C compared to 10°C. In 2007, the Q₁₀ parameter was 3.88. The R₁₀ parameter values were nearly identical between years (1.08 and 1.18 µmol CO₂ m⁻² s⁻¹). This indicates greater respiration in 2008 which corresponds to the higher temperatures 2008 growing season.
4.1.3 NEE and WT

Water availability is another important controlling factor on both GEP and ER. Both vascular and nonvascular species are vulnerable to moisture stress. Moss productivity is very sensitive to desiccation given that they do no have the means to control tissue water content (Silvola, 1990; Gignac and Vitt, 1994). Furthermore, vascular productivity can also be inhibited by drought with evidence to suggest that subarctic wetland plant species exhibit water conservation during times of water stress (Blanken and Rouse, 1996). However, WT heights were never far below the surface of the hollows in either year so it was assumed that there was adequate water availability to most vascular plant species throughout both the 2007 and 2008 measurement periods. Variation in soil moisture however will impact rates of heterotrophic and autotrophic respiration. The comparatively higher ER corresponded to comparatively lower WT throughout most of the 2008 growing season. Estimated cumulative ER was 510 g CO₂ m⁻² with an ER/GEP ratio of 0.62 in 2007 and 595 g CO₂ m⁻² with an ER/GEP ratio of 0.57 in 2008. Ecosystem respiration responded less to variations in temperature and water variability than GEP. Ecosystem respiration only increased 17% while GEP increased 26% between 2007 and 2008.
4.2 Net Ecosystem CO\textsubscript{2} Exchange During Each Phenological Period

4.2.1 Pre-Green NEE

The pre-green period is typically characterized by increasing air temperatures and PPFD, very little precipitation, and peak WT levels. Pre-green daily average GEP was -1.02 and -0.84 \(\mu\text{mol CO}_2 \text{ m}^{-2} \text{ s}^{-1}\) in 2007 and 2008, respectively. \(\sum\text{GEP}\) was -54 and -45 g CO\textsubscript{2} m\textsuperscript{-2} s\textsuperscript{-1} in 2007 and 2008, respectively. In 2008, the pre-green GEP-PPFD curve approaches \(GEP_{\text{max}}\) around 250 \(\mu\text{mol m}^{-2} \text{ s}^{-1}\). In 2007, the pre-green GEP-PPFD curve continues to increase throughout all PPFD values. This indicates a more productive ecosystem in 2007 which may have been a result of less water availability in 2008 with lower WT.

The monthly mean air temperature in May of 2007 was 2°C above the 30-year normal which may have led to earlier snowmelt and faster bryophyte development. The monthly mean air temperature in May of 2008 was slightly below normal which may have led to a later snowmelt. Furthermore, snow accumulation during the winter of 2007/2008 far exceeded that of 2006/2007 which may have lengthened snowmelt duration during spring of 2008. In 2008, pre-green average PPFD was greater than all 2007 periods. Pre-green average PPFD was 22\% greater in 2008 but this did not translate into greater productivity. However, the greater energy received during the pre-green period may have had a positive impact on subsequent periods.
4.2.2 Early-Green NEE

The early-green period is typically characterized by peak PPFD, increasing air temperatures and precipitation, and decreasing WT levels. Early-green daily average GEP was -2.48 and -3.26 µmol CO₂ m⁻² s⁻¹ in 2007 and 2008, respectively. ΣGEP was -330 and -433 g CO₂ m⁻² s⁻¹ in 2007 and 2008, respectively. Early-green GEP-PPFD curves indicate a more productive ecosystem in 2008. Early-green GEP-PPFD curves approach GEP_max around 1000 µmol m⁻² s⁻¹ in both years but GEP declines at high PPFD values in 2007. Light-use efficiency (α) during the early-green period is 38% greater in 2008 compared to 2007. The monthly mean air temperature in June of 2008 was 1.2°C above normal and 0.7°C below normal in 2007. Accumulated precipitation in June was 55 mm above normal in 2008 (100 mm) and 16 mm below normal in 2007 (29 mm). The warmer and wetter conditions during June of 2008 most likely enhanced development of the vascular species and maintained optimal bryophyte moisture content. The monthly mean air temperature in July of 2008 was 1.5°C above normal and 3.4°C above normal in 2007. Accumulated precipitation in July was 36 mm below normal in 2008 (20 mm) and 27 mm below normal in 2007 (29 mm). The warmer and drier conditions during July of 2007 may have led to the desiccation of nonvascular species and inhibited plant development. Average PPFD was 21% greater in 2008 which would have further assisted in plant development.
4.2.3 Late-Green NEE

The late-green period is typically characterized by decreasing PPFD, peak air temperatures, increasing precipitation, and lowest WT levels. Late-green daily average GEP was -2.75 and -3.32 µmol CO₂ m⁻² s⁻¹ in 2007 and 2008, respectively. ΣGEP was -366 and -441 g CO₂ m⁻² s⁻¹ in 2007 and 2008, respectively. Late-green GEP-PPFD curves also approach GEP_max around 1500 CO₂ m⁻² s⁻¹ in both years. The GEP-PPFD relationship is strongest during this period (r² = 0.98 in 2007 and r² = 0.98 in 2008) corresponding to peak plant development and maximum leaf area. Light-use efficiency (α) during the late-green period is 52% greater in 2008 compared to 2007. The monthly mean air temperature in August of 2008 was 3.0°C above normal and 0.3°C above normal in 2007. Accumulated precipitation in August was 80 mm above normal in 2008 (168 mm) and 23 mm below normal in 2007 (45 mm). Average PPFD was very similar in both years during the late-green period. The warmer and wetter conditions during August of 2008 most likely enhanced vascular species productivity and maintained optimal bryophyte moisture content.
4.2.4 Post-Green NEE

The post-green period is typically characterized by decreasing PPFD and air temperatures, peak precipitation, and increasing WT levels. Post-green daily average GEP was -1.41 and -1.88 µmol CO₂ m⁻² s⁻¹ in 2007 and 2008, respectively. ΣGEP was -75 and -100 g CO₂ m⁻² s⁻¹ in 2007 and 2008, respectively. Post-green GEP-PPFD curves approach GEP_max around 1000 µmol m⁻² s⁻¹ in both years. The GEP-PPFD relationship is stronger in 2008 (r² = 0.95) compared to 2007 (r² = 0.89) and light-use efficiency is 46% greater in 2008. The warmer air temperatures and increased rainfall during this period in 2008 along with physiological stress-free conditions prolonged the growing season well into September. Plant senescence most likely occurred earlier during the post-green period in 2007 due to increasing plant physiological stress resulting from the colder and drier conditions experienced late in the growing season. Average PPFD was 27% greater in 2008 which would have contributed to the lengthened growing season, increasing late-season productivity.
4.3 Annual CO₂ Exchange

4.3.1 Growing Season CO₂ Exchange

There was substantial net-CO₂ uptake during the measurement period in both 2007 and 2008. Almost all CO₂ flux studies from similar ecosystems report less growing season CO₂ sequestration than observed here and in some instances CO₂ efflux. The only study to report greater growing season CO₂ uptake from a similar ecosystem is close to Barrow, Alaska (Harazono et al., 2003). The results of Harazono et al. (2003) indicate that the wet sedge tundra ecosystem was a net sink of -593 g CO₂ m⁻² in 1999 and a sink of -384 g CO₂ m⁻² in 2000. Measurements of NEE during the growing seasons (DOY 164-238) of 1994 and 1996-1999 at this site found both CO₂ efflux (+76 g CO₂ m⁻²) and CO₂ uptake (-34 to -235 g CO₂ m⁻²).
4.3.2 Estimated Winter Season CO₂ Release

Carbon dioxide release during the winter months can potentially exceed CO₂ uptake during the growing season (Oechel et al., 1997; Fahnestock et al., 1999). Winter season efflux was estimated using the standard Q₁₀ relationship with average Q₁₀ and R₁₀ values between the two years and assuming constant Tₛ at -0.05 m of 0°C and -6.5°C. A constant -0.05 m peat temperature of 0°C represents will most likely overestimate winter release given that peat temperature ought to be several degrees below freezing for much of the winter. An average -0.05 m peat temperature of -6.5°C was recorded during the 2007/2008 winter season. For a peat temperature of 0°C, the estimated daily CO₂ release was calculated to be 1.00 g CO₂ m⁻² d⁻¹. Despite this expected overestimation, the ecosystem still remains a substantial CO₂ sink of -76 and -163 g CO₂ m⁻² in 2007 and 2008, respectively. For a peat temperature of -6.5°C, the estimated daily CO₂ release was calculated to be 0.39 g CO₂ m⁻² d⁻¹. Using this more accurate estimation of winter CO₂ release, the ecosystem was a CO₂ sink of -239 and -346 g CO₂ m⁻² in 2007 and 2008, respectively.
4.4 Water-Use Efficiency During Two Warm and Dry Periods

During both hot, dry periods, hourly averaged ET corresponds closely to hourly averaged VPD. However, hourly averaged values of $\alpha_{PT}$ decreased dramatically early in the morning and remain low throughout most of the day indicating surface moisture limitation. Priestley-Taylor evaporation coefficient values less than 1.26 indicates surface control on $Q_E$. However, hourly averaged Bowen ratio values remained low, i.e. $Q_H < Q_E$, indicating that the majority of heat input into the atmosphere was in latent form. These small Bowen ratio values are justified given that WT depths did not drop far below the surface of the hollows at any point during either period. Despite WT just below the surface of the hollows, the surface of the fen did not evapotranspire at or near the potential rate of evapotranspiration. Possible mechanisms for this surface control are through vascular stomatal closure and/or nonvascular desiccation and/or peat surface drying. Gross ecosystem productivity peaked during mid-morning hours and corresponded with maximum WUE and minimum $\alpha_{PT}$ but did not correspond with peak PPFD. A GEP peak before solar noon suggests moisture and/or heat stress. During these two hot, dry periods, it is assumed that the vascular species had adequate access to water given their extensive root systems penetrating below the WT; only vascular species inhabiting large hummocks may have experienced some form of moisture stress. It is also assumed that nonvascular species experienced varying degrees of dessication depending on their location within the microtopography of the ecosystem. There is evidence of water conservation in Carex species (Blanken and Rouse, 1996; Schraeder et al., 1998) and bryophyte/lichen desiccation inhibits primary productivity. Therefore, we
would attribute most of this surface control on surface peat drying and vascular stomatal control from species located on large hummocks.
4.5 Comparison of GEP-PPFD and ER-Ts, Modelling Parameters

Measurements of NEE can be partitioned into photosynthesis (GEP) and respiration (ER) (Stoy, 2006). Ecosystem respiration was a function of $T_s$ and its functionality was represented by the exponential $Q_{10}$ relationship. Gross ecosystem productivity was a function of PPFD and its functionality was represented by the rectangular hyperbola (Thornley and Johnson, 1990) which can be incorporated into peatland carbon balance models (e.g. Frolking et al., 2002). Current modelling efforts are now focusing more on biochemical models of photosynthetic assimilation (Farquhar et al., 1980; Medlyn et al., 2002) which are then incorporated into wetland ecosystem models (e.g. St-Hilaire et al., 2008).

A between year comparison of the light-use efficiency curves and their respective parameter values from each phenological period suggest a more productive ecosystem in 2008. Pre-green period parameter values ($\alpha$ and $\text{GEP}_{\max}$) were slightly greater in 2007 while during the early-, late- and post-green periods, $\alpha$ was about 45% greater in 2008. The light-use efficiency curves suggest a more physiological stress-free ecosystem during the 2008 measurement period corresponding with higher $T_a$, prolonged growing season, greater precipitation, greater irradiance, and lower WT heights.
4.6 Comparison of GEP-PPFD Parameter Values and ΣNEE

Calculated light-use efficiency (α) and maximum photosynthetic capacity (GEP\textsubscript{max}) parameter values were similar to parameter values calculated at this site from previous years (Table 14). Calculated α ranged from 4.75 to 24.06 mmol CO\textsubscript{2} mol\textsuperscript{-1} PPFD during the 2007 and 2008 measurement periods which were slightly higher than α values calculated at this site during the mid-to-late 1990s (Table 14). Calculated GEP\textsubscript{max} ranged from 2.96 to 11.23 µmol CO\textsubscript{2} m\textsuperscript{-2} s\textsuperscript{-1} during the 2007 and 2008 measurement period which were very similar to values calculated at this site during the mid-to-late 1990s (Table 14). Overall, calculated α and GEP\textsubscript{max} parameter values from the 2007 and 2008 measurement periods compared well to previously calculated values from this site.

Calculated α and GEP\textsubscript{max} values were also quite similar to values calculated at other similar wetland sites (Table 14). Calculated α values from other similar wetland sites ranged from as little as 0.0206 mmol CO\textsubscript{2} mol\textsuperscript{-1} PPFD to as high as 500 mmol CO\textsubscript{2} mol\textsuperscript{-1} PPFD (Table 14). Calculated GEP\textsubscript{max} values from other similar wetland sites ranged from as little 0.58 µmol CO\textsubscript{2} m\textsuperscript{-2} s\textsuperscript{-1} to as high as 25.59 µmol CO\textsubscript{2} m\textsuperscript{-2} s\textsuperscript{-1} (Table 14). Overall, calculated α and GEP\textsubscript{max} parameter values from the 2007 and 2008 measurement periods compared well to calculated parameter values from wetlands of similar latitude.

Calculated ΣNEE during both the 2007 and 2008 measurement periods were quite high compared to other wetland studies with similar measurement periods (Table 14). Almost all other studies reported less CO\textsubscript{2} uptake during the growing season (Table 14). However, there were three sites that reported similar or greater CO\textsubscript{2} uptake, two of those
sites located to the south of the Churchill fen (Glenn et al., 2006; Lafleur et al., 2003) and one of those sites located to the north of the Churchill fen (Harazono et al., 2003) (Table 14).

Prior to this study, the highest CO₂ uptake recorded at this Churchill fen site was -235 g CO₂ m⁻² (Jun 13-Aug 26) during a wetter and cooler than normal growing season in 1996 (Griffis and Rouse, 2001). Both the 2007 and 2008 growing seasons at the Churchill fen were warmer than normal. The 2008 growing season was also wetter than normal. Griffis and Rouse (2001) developed an empirical model of NEE using data from five growing seasons at the Churchill fen and sensitivity of NEE to changes in Tₐ was explored in all years of recorded data. In 1996, modelled NEE was calculated to increase by -234 g CO₂ m⁻² given a Tₐ increase of 4°C with all other things being equal (Griffis and Rouse, 1996). This expected increase would exceed the NEE calculated for the 2008 measurement period. Therefore, the large CO₂ uptake recorded during the 2008 growing season is justified given the warm and wet conditions during the measurement period.
Table 14: Comparison of rectangular hyperbolic light-use efficiency parameter values (α and GEP$_{\text{max}}$) and cumulative net ecosystem CO$_2$ exchange (ΣNEE) by other studies at similar wetland sites and this site.

<table>
<thead>
<tr>
<th>Source</th>
<th>Site Location</th>
<th>α</th>
<th>GEP$_{\text{max}}$</th>
<th>ΣNEE</th>
<th>Study Period</th>
<th>Years</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aurela et al. (1998)</td>
<td>Open flark fen (69.1°N)</td>
<td>11-20</td>
<td>3-7</td>
<td>N/A</td>
<td>Aug 15-Sep 13</td>
<td>1995</td>
</tr>
<tr>
<td>Aurela et al. (2001)</td>
<td>Open flark fen (69.1°N)</td>
<td>0.02-0.19</td>
<td>3.8-11.3</td>
<td>-188</td>
<td>Jun 15-Aug 26</td>
<td>1997</td>
</tr>
<tr>
<td>Bubier et al. (2003)</td>
<td>Poor fen (43.2°N)</td>
<td>4-117</td>
<td>2.58-25.59</td>
<td>N/A</td>
<td>Jun 1-Sep 30</td>
<td>2000-2001</td>
</tr>
<tr>
<td>Frolking et al. (1998)</td>
<td>8 fen sites</td>
<td>23</td>
<td>10.8</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Frolking et al. (2002)</td>
<td>Mer Bleue bog-PCARS (45.4°N)</td>
<td>20</td>
<td>variable</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Glenn et al. (2006)</td>
<td>Poor and rich fen (54.5°N &amp; 55.5°N)</td>
<td>17-34</td>
<td>5.6-12.1</td>
<td>-330 to -113</td>
<td>May 1-Oct 31</td>
<td>2004</td>
</tr>
<tr>
<td>Kwon et al. (2006)</td>
<td>Moist tussock tundra (71.3°N)</td>
<td>N/A</td>
<td>N/A</td>
<td>-7 to 223</td>
<td>Jun 1-Aug 31</td>
<td>1993-2003</td>
</tr>
<tr>
<td>Lafleur &amp; Humpreys (2007)</td>
<td>Treeless tundra site (64.9°N)</td>
<td>5-37</td>
<td>0.58-6.94</td>
<td>-32 to -61</td>
<td>May 15-Aug 31</td>
<td>2004-2006</td>
</tr>
<tr>
<td>Laurila et al. (2001)</td>
<td>3 European fens (69.1, 69.8, &amp; 74.5°N)</td>
<td>26-34</td>
<td>6.8-10</td>
<td>N/A</td>
<td>Jul 25-Jul 29</td>
<td>1997</td>
</tr>
<tr>
<td>Vourlitis &amp; Oechel (1997)</td>
<td>Wet herbaceous tundra (70.3°N)</td>
<td>4-18</td>
<td>0.72-6.64</td>
<td>-102 to -49</td>
<td>May 29-Sep 16</td>
<td>1994-1995</td>
</tr>
<tr>
<td>Whiting (1994)</td>
<td>Coastal &amp; inland fens (51.5°N)</td>
<td>0.7-30</td>
<td>0.5-8.2</td>
<td>N/A</td>
<td>Jun 11-Aug 21</td>
<td>1990</td>
</tr>
<tr>
<td></td>
<td>Churchill fen (58.7°N)</td>
<td>5.69-23.58</td>
<td>2.96-10.4</td>
<td>-343 (± 79)</td>
<td>Jun 6-Sep 11</td>
<td>2007</td>
</tr>
<tr>
<td></td>
<td>Churchill fen (58.7°N)</td>
<td>4.75-24.06</td>
<td>3.39-11.23</td>
<td>-450 (± 87)</td>
<td>Jun 6-Sep 11</td>
<td>2008</td>
</tr>
</tbody>
</table>

Units for light-use efficiency (α) are mmol CO$_2$ mol$^{-1}$ PPFD. Units for maximum photosynthetic capacity (GEP$_{\text{max}}$) are µmol CO$_2$ m$^{-2}$ s$^{-1}$. Units for cumulative net ecosystem CO$_2$ exchange (ΣNEE) are g CO$_2$ m$^{-2}$. N/A indicates value not available.
4.7 Climate Change and NEE

Northern high latitude warming will inevitably lead to changes in the duration and start/end dates of the growing season (Maxwell, 1992, 1996). In a comparison study of 12 northern peatland sites, Lund et al. (2009) found growing season length to be an important variable in explaining between-site variation of both GEP and ER. According to their linear relationship, during the months of June, July, and August (JJA) the Churchill sedge fen should have reported an average GEP of -1.27 g C m\(^{-2}\) d\(^{-1}\) in 2007 (GS\(_{\text{length}}\) = 77 days) and -1.54 g C m\(^{-2}\) d\(^{-1}\) in 2008 (GS\(_{\text{length}}\) = 91 days). Corresponding ER is expected to be 0.98 g C m\(^{-2}\) d\(^{-1}\) in 2007 and 1.18 g C m\(^{-2}\) d\(^{-1}\) in 2008. Both the measured GEP and ER from the 2007 and 2008 measurement periods were greater than the expected GEP and ER from Lund et al. (2009). Measured mean GEP was -2.42 g C m\(^{-2}\) d\(^{-1}\) in 2007 and -2.96 g C m\(^{-2}\) d\(^{-1}\) in 2008 and measured mean ER was 1.48 g C m\(^{-2}\) d\(^{-1}\) in 2007 and 1.66 g C m\(^{-2}\) d\(^{-1}\) in 2008.

A prolonged growing season at these peatland environments is expected to enhance both the productive capacity of vegetation and the rate of peat decomposition. Gross ecosystem productivity is expected to increase more with a prolonged growing season as compared to ER (Lund et al., 2009). Our results support this prediction with 21% greater mean daily GEP and only 10% greater mean daily ER corresponding to an 18% longer growing season in 2008 compared to 2007. Empirical models from this site predict enhanced ecosystem CO\(_2\) sequestration during wetter and warmer conditions (Waddington et al., 1998; Griffis and Rouse, 2001). Griffis et al. (2000) predicted that...
net uptake of CO$_2$ could triple with a small decrease in mean water table position at this same Churchill sedge fen site. Our results support this prediction with the enhanced CO$_2$ uptake recorded in 2008 accompanied by 252 mm more precipitation and $T_a \sim 1^\circ$C greater in 2008 compared to 2007.
Measurements of CO$_2$ and energy fluxes were collected at a subarctic sedge fen in the Hudson Bay Lowland near to Churchill, Manitoba, Canada utilizing the eddy covariance technique. Data were collected during the growing seasons of 2007 (DOY: 157-254) and 2008 (DOY: 157-268). Both growing seasons were warmer (~1-2º) than the historical average (1971-2000). The 2008 growing season was wetter than the historical average but WT never dropped far below the surface of the hollows in either growing season. The growing season was estimated to have commenced earlier and ended later in 2008 (DOY 175-265; 91 days) compared to 2007 (DOY 183-239; 77 days). The effect of the warmer temperatures and increased rainfall during the 2008 growing season was observed in the CO$_2$ fluxes.

Maximum daily NEE occurred on DOY 217 (-9.5 g CO$_2$ m$^{-2}$ d$^{-1}$) in 2007 and on DOY 190 (-12.9 g CO$_2$ m$^{-2}$ d$^{-1}$) in 2008. The fen acted as a net-CO$_2$ sink for each measurement period of -343 (± 79) g CO$_2$ m$^{-2}$ in 2007, and -450 (± 87) g CO$_2$ m$^{-2}$ in 2008. ΣGEP was -826 (± 190) g CO$_2$ m$^{-2}$ in 2007 and -1020 (± 197) g CO$_2$ m$^{-2}$ in 2008. ΣER was 510 (± 117) g CO$_2$ m$^{-2}$ in 2007 and 570 (± 109) g CO$_2$ m$^{-2}$ in 2008. Thus, the greater CO$_2$ sink measured during the 2008 growing season can be attributed to increased productivity most likely resulting from greater overall plant health and increased LAI. This also indicates that the productivity of the ecosystem is inhibited by high WT and low temperatures which decreases nutrient mineralization and restricts vegetation distribution. An expected overestimation of wintertime CO$_2$ release was calculated using the standard
\( Q_{10} \) relationship and a constant soil temperature of 0°C. Despite this expected overestimation the ecosystem still remained a substantial net-CO\(_2\) sink in both years.
REFERENCE LIST


