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Environmental Research Letters

LETTER

Can boreal peatlands with pools be net sinks for CO$_2$?

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Abstract

Peatland open-water pools, a common feature on temperate to subarctic peatlands, are sources of carbon (C) to the atmosphere but their contribution to the net ecosystem carbon dioxide exchange (NEE-CO$_2$) is poorly known; there is a question as to whether peatlands with pools are smaller sinks of atmospheric C, or even C-neutral, compared to other peatlands. We present growing season NEE-CO$_2$ measurements using the eddy covariance technique in a peatland with pools. We found the maximum photosynthetic uptake and ecosystem respiration rates at 10 °C to be in the lower range of the published data. The lower total vegetation biomass, due to the presence of pools, reduced CO$_2$ uptake during day and the autotrophic component of ecosystem respiration. The low CO$_2$ uptake combined with reduced CO$_2$ loss resulted in the site being a net sink for CO$_2$ of a similar magnitude as other northern peatlands despite the inclusion of pools.

1. Introduction

Peatland open water pools are autogenic features that form through interaction between the biotic components of the ecosystem. The water bodies are, as opposed to the vegetated portions of peatland sites, net sources of carbon (C) to the atmosphere (23–419 gC m^{-2} yr^{-1}) (Hamilton *et al* 1994, Waddington and Roulet 2000, Repo *et al* 2007, McEnroe *et al* 2009, Pelletier *et al* 2014). This release of C is due to peat decomposition at their bottom, limited emergent vegetation to uptake CO$_2$, and microbial and photo-degradation of dissolved organic carbon (DOC). The published rates of C release from water bodies on peatlands are of the same magnitude, but with an opposite sign, as the published net ecosystem carbon balance (NECB) for peatlands without pools (e.g. from a source of 14 to a sink −101 gC m^{-2} yr^{-1}) (Roulet *et al* 2007, Nilsson *et al* 2008, Billett *et al* 2010, Koehler *et al* 2011, Olefeldt *et al* 2012). Peatlands with pools are found from temperate to subarctic regions in both the northern and southern hemispheres (Glaser 1999) and are of varying age (e.g., Foster and Wright 1990, Beilman *et al* 2009, van Bellen *et al* 2011,

Magnan and Garneau 2014); the long-term C accumulation in the vegetated areas of these peatlands has to exceed the C loss from the pools. However, assuming peatlands with pools have a similar uptake as those without pools could result in a significant overestimation of the C uptake attributed to peatlands. Pools form from differential biomass accumulation and decomposition and their development is influenced by climate, topography, and geographical setting (e.g., Foster and Wright 1990, Belyea and Lancaster 2002, Belyea 2007, Eppinga *et al* 2009, Morris *et al* 2013). Pool depth appears to vary from <0.5 to >2 m and width from 1 m to >100 m (e.g., Foster and Wright 1990, Karofeld and Tõnisson 2012). Despite their wide geographic coverage, there are only a few estimates of the surface area of peatlands covered by pools. In the Hudson Bay Lowlands, pool coverage is >40% in some areas (Roulet *et al* 1994), >50% in fens in northeastern Quebec, Canada (White 2011), and between 5 and 40% in some of the major peatland types in Russia (Botch *et al* 1995). Recently there has been an effort to include peatlands (e.g., Wania *et al* 2009, Kleinen *et al* 2012, Spahni *et al* 2012, Wu *et al* 2012) in models that simulate climate–C

connections, but the resolution of these models is far too coarse to include pools. Therefore it is relevant and timely to determine if the C exchange from peatlands with pools is different than that of peatlands without pools to determine if the simple generalized model parameterization might be used for peatlands with pools.

Measurements of net ecosystem carbon dioxide exchange (NEE-CO_2) using the eddy covariance (EC) method have been made in several peatlands in temperate, boreal and surbarctic regions, covering multiple years of continuous measurements (e.g., Aurela *et al* 2004, Roulet *et al* 2007, Sagerfors *et al* 2008). However, these peatlands have relatively homogeneous surface vegetation (e.g., Lafleur *et al* 2003, Aurela *et al* 2009) and no pools, with the possible exception of the measurements from Kaamanen in northern Finland where there are ephemeral pools (Aurela *et al* 2001, 2002, 2004). To our knowledge, no NEE-CO_2 measurements have been reported for peatland with deeper and permanent open water pools. The magnitude of the published annual release of C from open water pools raises the question as to whether the generalized uptake figures for peatlands without pools apply to peatlands with permanent open-water pools. Considering the efforts to integrate peatlands into global climate models, it is important that the C exchange from different peatland types be documented in order to provide guidance on how to parameterize these models (Frolking *et al* 2009).

Based on the reported net loss of CO_2 from pools (e.g., Waddington and Roulet 2000, Pelletier *et al* 2014) and the NEE-CO_2 uptake for vegetated peat surfaces (e.g., Lafleur *et al* 2003, Sagerfors *et al* 2008), we hypothesize that peatlands with pools are either NEE-CO_2 neutral or a smaller sink for CO_2 during the growing than peatlands without pools. Here we present the results of one growing season (May–October) of NEE-CO_2 measurements in a boreal ombrotrophic peatland with pools and compare these results with those reported in the literature for peatlands without pools.

2. Study site and methods

We measured the NEE-CO_2 using the EC technique (Baldocchi 2003) from 15 May to 10 October 2012 on a peatland located on the Manicouagan peninsula (49° 08'N, 68°17'W; altitude: 19 m) 8 km south of Baie Comeau, on the north shore of the St. Lawrence River in Quebec, Canada. The peatland is a raised bog that covers approximately 600 ha with a surface pattern that consists of hummocks, lawns and pools. *Sphagnum fuscum* (Schimp.) H.Klinggr., *Chamaedaphnee calyculata* (L.) Moench, dwarf *Picea mariana* (Miller) BSP and *Rhododendron groenlandicum* (Oeder) Kron and Judd dominate the hummocks, while the vegetation on the lawns is mainly composed of *Sphagnum*

rubellum Wils., *Andromeda polifolia* L., *Vaccinium oxycoccos* L. and sedges (*Eriophorum spp.*) (Simard 1976, Magnan and Garneau 2014). The pools are free of vegetation except for some *Nuphar lutea* (L.) Sm. found in the shallow sections (<1 m depth). The pool surface area was evaluated using a supervised classification performed on a geometrically rectified and orthorectified Worldview-2 image. The pools cover approximately 7% of the entire peatland surface but they cover 22% of the surface within 100 m of the EC tower. Footprint estimation analysis reveals that 90% of the CO_2 flux was provided on average by the area within 108 m (SD ± 12 m) of the tower location (Kljun *et al* 2004, Eddypro V5.1.0, LI-COR, Lincoln, NE). The pools are not uniformly distributed around the EC tower with 37% pool coverage found between 180° and 360° azimuth, compared to 9% between 0° and 180° (figure 1). The 30-year climate normal (1981–2010) mean annual temperature is 1.7 °C and mean annual precipitation is 1001 mm. The coldest and warmest months are January and July with mean daily temperature of −14.3 and 15.6 °C respectively. On average, 34% of the annual precipitation falls as snow, with average snowfall of 303 mm [Environment Canada, data available at http://climate.weatheroffice. gc.ca]. In 2012, the pools were ice-covered from mid-November to the end of April, and the vegetated area was frozen to a depth of ∼0.1 m for four months of the year.

The EC system consisted of a fast response three-dimensional sonic anemometer (CSAT-3, Campbell Scientific, Edmonton, Canada), a fine-wire thermocouple (FW05, Campbell Scientific, Edmonton, Canada), and an enclosed CO_2/H_2O analyzer (LI-7200, LI-COR, Lincoln, NE). The instruments were mounted on a tripod 2.5 m above the surface of the peatland. The variables used to calculate the flux were recorded and stored on a 4 GB industrial grade USB flash drive using an analyzer control unit (LI-7550, LI-COR, Lincoln, NE) at 10 Hz. Air density fluctuations due to temperature were accounted for using a posteriori correction from a revision of the WPL formulation (Ibrom *et al* 2007). The 30 min CO_2 fluxes were computed from the 10 Hz data using the Eddy-Pro processing software (V5.1.0, LI-COR, Lincoln, NE). The CO_2 fluxes were derived from the covariance between vertical wind speed and CO_2 mixing ratio (Burba *et al* 2012). A two-dimensional coordinate rotation was applied. The EC CO_2 data were cleaned for quality flags output by the EddyPro processing software (Mauder and Foken 2004). The CO_2 data showing uptake at night were removed using a photosynthetically active radiation (PAR) threshold of <20 μmol m^{-2} s^{-1} (Lafleur *et al* 2003). Following this step, the CO_2 data were separated into day and night, and data were discarded if deviating more than ±3 standard deviations of the monthly means (Baldocchi *et al* 1997). The nighttime NEE-CO_2 were plotted (not shown) against friction velocity ($u^\star$), and a threshold
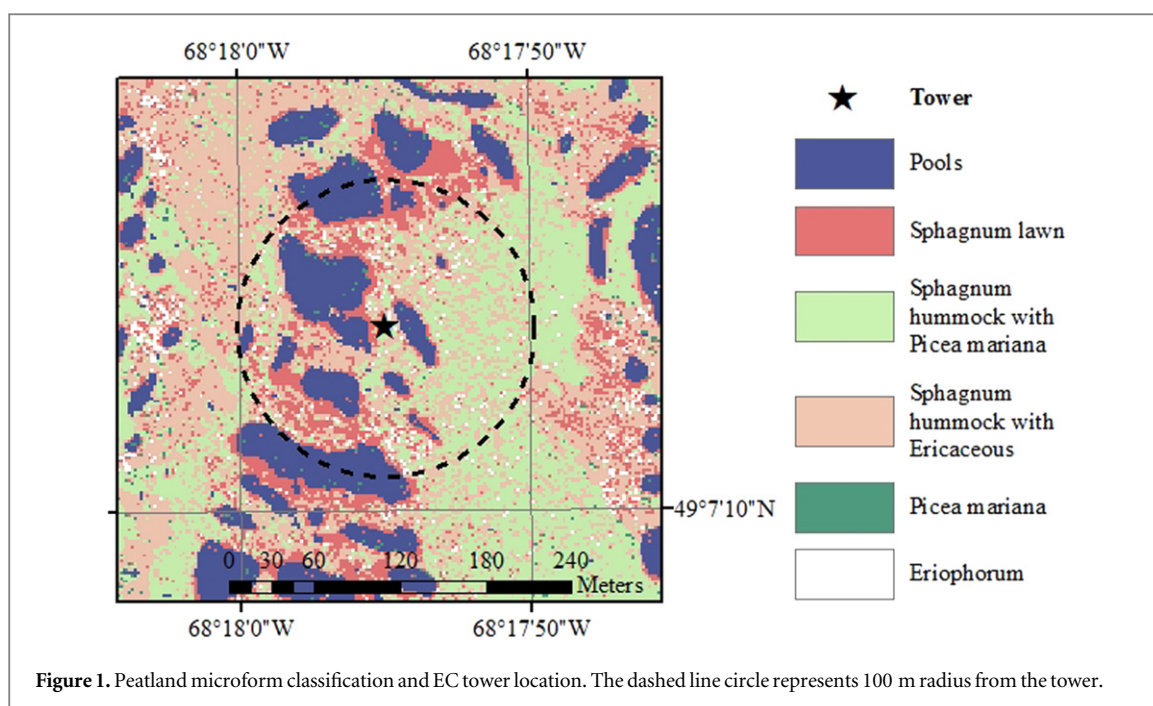
Figure 1. Peatland microform classification and EC tower location. The dashed line circle represents 100 m radius from the tower.

of $0.1 \, \text{m s}^{-1}$ was used to identify insufficient turbulent mixing to assess reliable fluxes (e.g., Lafleur *et al* 2001); data not meeting the criteria were discarded. The cleaning procedure resulted in 43% of the fluxes being rejected. Due to the complexity of the landscape surrounding the EC tower, no gap filling procedure was applied to the data set for the analysis we present below. The monthly daily average NEE-CO_2 was therefore evaluated by averaging the mean monthly diurnal pattern of NEE-CO_2 presented in figure 3. The monthly NEE_{max} was evaluated by averaging the individual NEE-CO_2 measurements for PAR > $1000 \, \mu\text{mol m}^{-2} \, \text{s}^{-1}$. The CO_2 fluxes are presented following the micrometeorological convention where an uptake by the ecosystem is represented by a negative flux, while a loss of CO_2 to the atmosphere is represented by a positive flux.
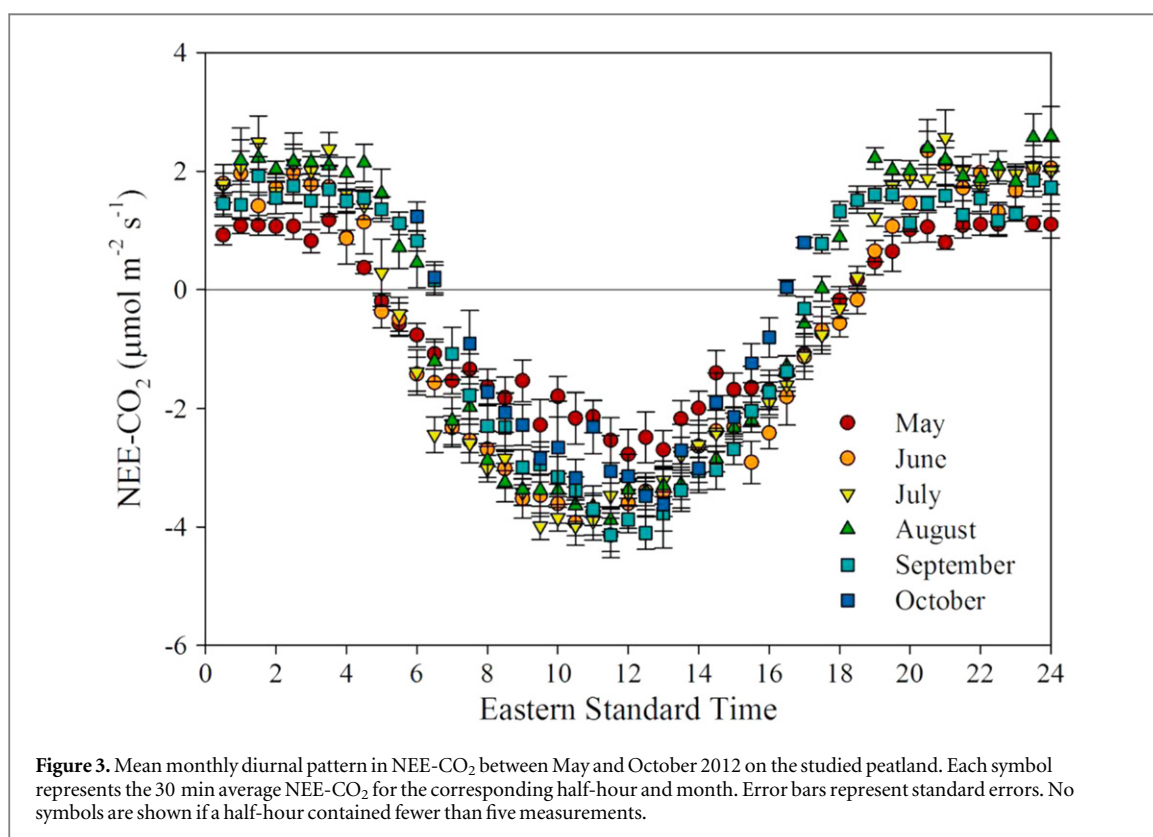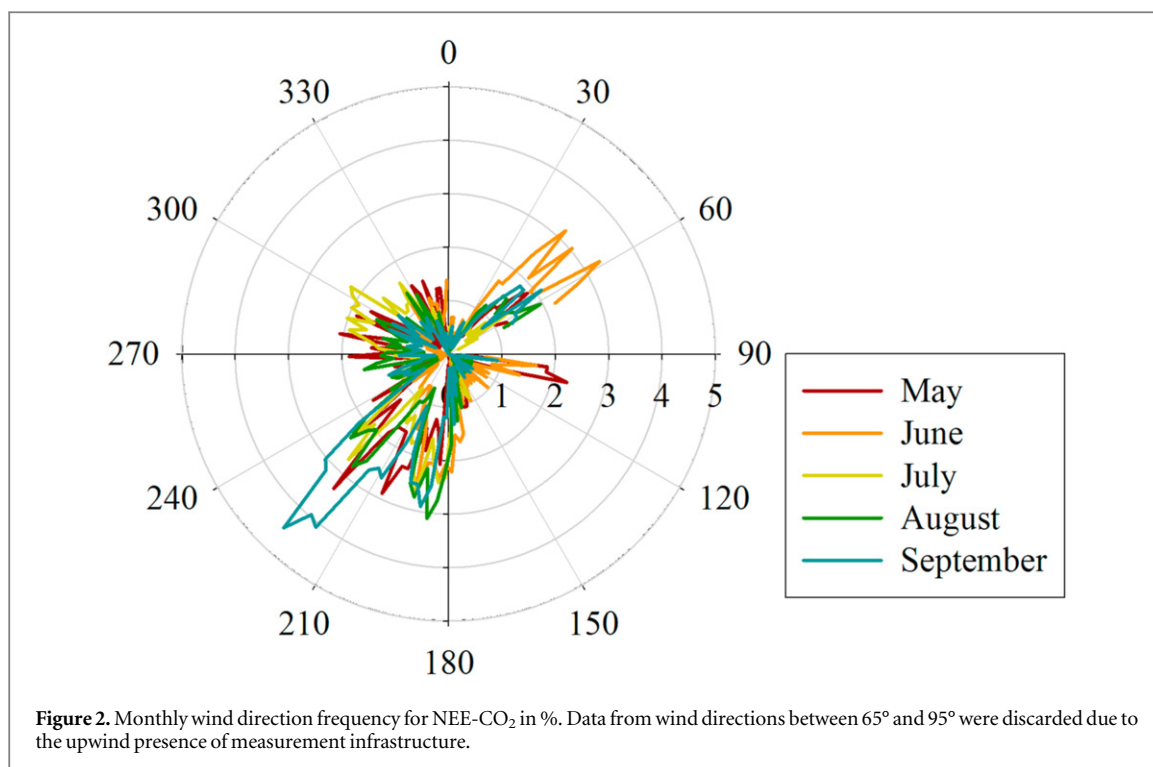
Environmental measurements were made every 5 s throughout the study period and averaged every 30 min. The variables measured included net radiation (CNR4, Kipp and Zonen, Delft, Netherlands), PAR (LI-190SA, LI-COR, Lincoln, NE), air temperature and relative humidity (HMP-45C, Vaisala, Helsinki, Finland), wind speed and direction (05103-10, RM-Young, Traverse City, MI) and precipitation (TE525M tipping bucket gauge, Texas Electronics, Dallas, TX).

3. Results

The 2012 monthly mean air temperatures between May and October were above the 30-year normal (1981–2010) [Environment Canada, data available at http://climate.weatheroffice.gc.ca]. The average monthly temperatures were higher by 1.0–2.4 °C with largest differences observed in August. These differences represent 0.9–2.2 times the standard deviation from the normal monthly average temperature. July precipitation was approximately half the normal value while October precipitation was double. Despite the warmer and drier conditions in July, the vegetation at the site showed no sign of desiccation.

The NEE-CO_2 measurements made between May and October 2012 covered the peatland surface between wind directions 180°–240° (36%), 270°–360° (25%), and 30°–60° (12%) (figure 2). The same wind directions dominated for nighttime ecosystem respiration (ER = NEE-CO_2 for PAR < $20 \, \mu\text{mol m}^{-2} \, \text{s}^{-1}$). The dominant wind directions were also relatively constant between months with the exception of June where the contribution from 30° to 60° was more important (22%). The monthly average diurnal trends in NEE-CO_2 showed CO_2 uptake during the day and CO_2 release at night (figure 3). The ER and NEE_{max} (NEE-CO_2 when PAR > $1000 \, \mu\text{mol m}^{-2} \, \text{s}^{-1}$) varied statistically ($p < 0.05$) between months over the measurement period (figure 4). The monthly average ER rate increased from early (May) to mid-growing season (July–August), before decreasing until October (figure 4). The monthly average NEE_{max} increased from early to late growing season, reaching a maximum uptake of $-4.1 \, \mu\text{mol m}^{-2} \, \text{s}^{-1}$ in September (figure 4). Overall, the monthly mean daily NEE-CO_2 flux showed uptake for all months with a range of -1.02 (SE ± 0.04) to -2.76 (±0.06) g $CO_2 \, \text{m}^{-2} \, \text{d}^{-1}$ and was higher in the first half of the growing season (May–July) (figure 4). The mean daily uptake for the entire study period was -1.84 g $CO_2 \, \text{m}^{-2} \, \text{d}^{-1}$. Data were binned by direction to differentiate the signals from sectors with different pool coverage. However, because of the proximity of the Saint Lawrence River
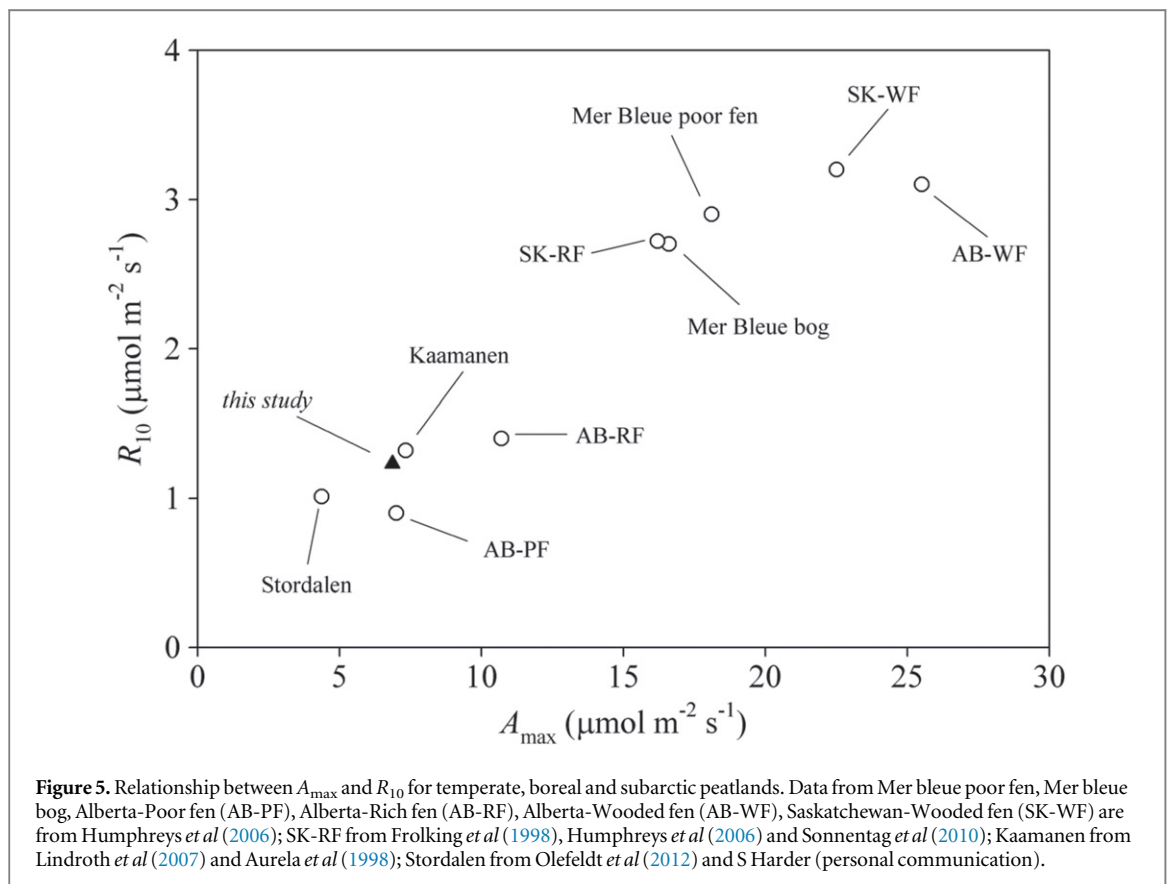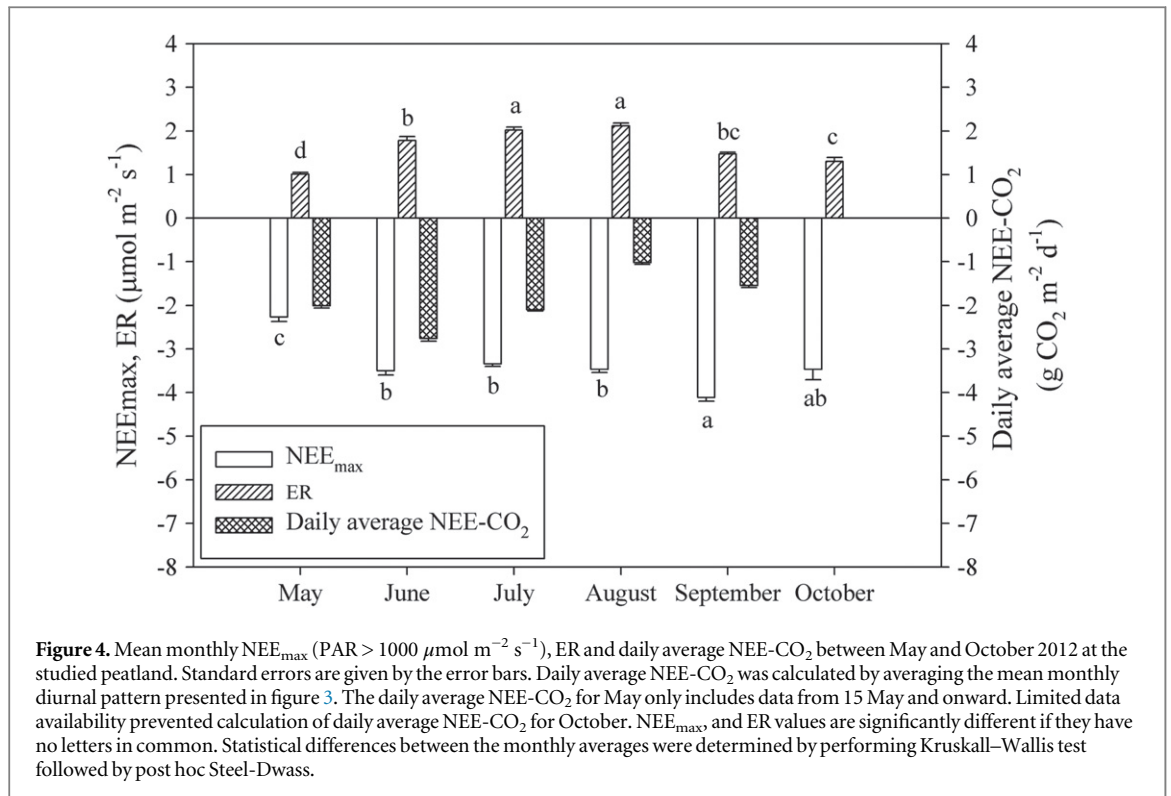
Figure 2. Monthly wind direction frequency for NEE-CO$_2$ in %. Data from wind directions between 65° and 95° were discarded due to the upwind presence of measurement infrastructure.

Figure 3. Mean monthly diurnal pattern in NEE-CO$_2$ between May and October 2012 on the studied peatland. Each symbol represents the 30 min average NEE-CO$_2$ for the corresponding half-hour and month. Error bars represent standard errors. No symbols are shown if a half-hour contained fewer than five measurements.

and the Gulf of Saint Lawrence, easterly winds generally bring clouds and rainy conditions and lower CO$_2$ exchange rates are typically measured during such conditions. Therefore, different processes (lower daytime PAR; presence of pools) yield numerically similar fluxes and the analysis of variability in fluxes by wind sector is compromised. Similarly, sorting ER by wind direction resulted in some bins having a very small number of data reducing the ability for statistical analysis.

4. Discussion

This study is the first to report EC NEE-CO$_2$ measurements made over a boreal peatland with permanent

Figure 4. Mean monthly NEE$_{max}$ (PAR > 1000 μmol m^{-2} s^{-1}), ER and daily average NEE-CO$_2$ between May and October 2012 at the studied peatland. Standard errors are given by the error bars. Daily average NEE-CO$_2$ was calculated by averaging the mean monthly diurnal pattern presented in figure 3. The daily average NEE-CO$_2$ for May only includes data from 15 May and onward. Limited data availability prevented calculation of daily average NEE-CO$_2$ for October. NEE$_{max}$, and ER values are significantly different if they have no letters in common. Statistical differences between the monthly averages were determined by performing Kruskall–Wallis test followed by post hoc Steel-Dwass.

Figure 5. Relationship between A_{max} and R_{10} for temperate, boreal and subarctic peatlands. Data from Mer bleue poor fen, Mer bleue bog, Alberta-Poor fen (AB-PF), Alberta-Rich fen (AB-RF), Alberta-Wooded fen (AB-WF), Saskatchewan-Wooded fen (SK-WF) are from Humphreys *et al* (2006); SK-RF from Frolking *et al* (1998), Humphreys *et al* (2006) and Sonnentag *et al* (2010); Kaamanen from Lindroth *et al* (2007) and Aurela *et al* (1998); Stordalen from Olefeldt *et al* (2012) and S Harder (personal communication).

pools. We found that the monthly average diurnal trends in NEE-CO$_2$ followed a pattern similar to other peatland ecosystems (Humphreys *et al* 2006), *Typha angustifolia* Marsh (Bonneville *et al* 2008) or forested ecosystems (Loescher *et al* 2003), where CO$_2$ uptake is observed during the day and CO$_2$ is released during the night (figure 3). The maximum photosynthetic uptake (A_{max}) calculated using a rectangular hyperbola relationship between GEP and PAR (see Frolking *et al* 1998), and the ER calculated for an air

Table 1. Mean June–September daily average NEE-CO_2 for the Petite Rivière peatland and other boreal and subarctic peatlands. Data from the Kamanen, Lompolojänkkä, Fäjemyr and Siikaneva were extracted from figures in the respective papers.

Peatland site	g CO_2 m^{-2} d^{-1}	Number of growing season	Source
Petite Riviere, Canada	−1.83	1	This study
Mer Beue bog, Canada	−1.54 to −2.84	4	Lafleur *et al* 2003
Degerö Stormyr, Sweden	−2.05 to −2.59	3	Sagerfors *et al* 2008
Kaamanen, Finland	−1.51 to −3.86	3	Aurela *et al* 2001, 2002, Lindroth *et al* 2007
Lompolojänkkä, Finland	−4.11 to −5.20	3	Aurela *et al* 2009
Fäjemyr, Sweden	−1.88	1	Lund *et al* 2007
Siikaneva, Finland	−2.70	1	Lindroth et al 2007

temperature of 10 °C (R_{10}) (Lloyd and Taylor 1994) were in the lower range of values for northern peatlands (figure 5). This means, that despite the presence of pools, the studied peatland has lower ER than other peatlands. The R_{10} we found is similar to the Stordalen palsa mire ($R_{10} = 1.01\ \mu$mol m^{-2} s^{-1}) (Olefeldt *et al* 2012) that is experiencing permafrost thaw and the Kaamanen subarctic mesotrophic fen ($R_{10} = 1.32\ \mu$mol m^{-2} s^{-1}) (Lindroth *et al* 2007), which has ephemeral pools in the spring and early summer (Heikkinen *et al* 2002). The autotrophic component of ER, which is generally about the same magnitude or larger than heterotrophic respiration in peatlands (Silvola *et al* 1996, Moore *et al* 2002) is eliminated for those portions of the peatland with pools. The presence of pools on the peatland can explain both the lower ecosystem A_{max} and R_{10}. Because of the absence of significant CO_2-fixing vegetation in the pools and their constant release of CO_2 to the atmosphere (Pelletier *et al* 2014), pool surfaces reduce the maximum photosynthetic uptake and respiration at the ecosystem level.

Despite the lower maximum photosynthetic uptake and respiration rates, the measured mean daily NEE-CO_2 for June–September (−1.83 g CO_2 m^{-2} d^{-1}) is within the range of published mean daily NEE-CO_2 measured in pool-free peatlands (−1.51 to −5.20 g CO_2 d^{-1}; table 1). This suggests that the lower photosynthetic rates measured at our site were offset by lower loss through ER, making this peatland with pools a net sink for CO_2 for the 2012 growing season, in the same range as that of peatlands without pools. It is unknown how the higher than normal temperatures observed during the measurement period affected the ecosystem level NEE-CO_2. Pelletier *et al* (2014) observed a strong positive correlation between pool water temperature and their C fluxes at the same site suggesting that pool C release may have been greater than 'normal' during the 2012 growing season.

Our results refute our hypothesis: the study peatland including its pools is not C-neutral nor a smaller sink for CO_2 during the growing season than what has been observed in other peatlands. This more generally suggests that the presence of pools on a northern peatland does not necessarily reduce the C sink potential. Olefeldt *et al* (2012) showed that low productivity combined with lower ER led to the NECB of a permafrost peatland having a similar net overall sink to boreal peatlands. For the permafrost peatland, the combined effect of limited vegetation biomass, low ER linked to the presence of permafrost, and extended winter periods still resulted in an average NECB of 56 gC m^{-2} yr^{-1}. In our studied peatland, the pools play a similar role in reducing the vegetation biomass therefore reducing both photosynthesis and autotrophic respiration. While the low ER in a permafrost-affected landscape is probably more due to lower soil respiration because of the low temperatures, the effect of the pools on ER is likely experienced through a decrease in the ecosystem autotrophic respiration. Simultaneously, chamber measurements of CO_2 exchange performed over the different microforms found on the studied site showed high CO_2 uptake on *Sphagnum* hummocks with *P mariana* (Pelletier *et al* in review). These high CO_2 uptake rates combined with surface coverage of this microform (figure 1) could represent an explanation as to why the vegetated surface offset the CO_2 loss from the pools (Pelletier *et al* in review). Winter CO_2 loss from peatlands represents an important part of the annual budget (Aurela *et al* 2002). Although we did not do winter measurements, the cold season CO_2 loss is likely to be low since the R_{10} value is low (figure 5) and cold temperatures persist for more than five months of the year. Even without winter measurements we are confident that the studied peatland is a net sink for CO_2. Using the NEE-CO_2 data from the Mer Bleue temperate bog (Humphreys *et al* 2014) in place of the periods January–April and November–December, and assuming that May and October are CO_2 neutral (in reality likely a weak sink), we found our site to be a net annual sink of 48.8 g CO_2 m^{-2} yr^{-1}. This estimation is conservative considering that the winter ER is likely greater at Mer Bleue because of the warmer peat temperatures and the absence of pools.

5. Conclusion

The results from the present study suggest that peatlands with pools can be net sinks for CO_2 at the ecosystem level during the growing season and potentially on an annual basis though we did not test this directly. Although the pools at our site represented net

sources of CO_2 to the atmosphere, the reduced ecosystem CO_2 uptake capacity is compensated by the limited CO_2 loss through respiration. This study is the first to present spatially integrated NEE-CO_2 for a peatland with pools; we present data from a single growing season and for one specific site, which is an example of peatland with pools. The representativeness of our site and results will only be determined if our work stimulates others to do the same sort of measurements in other peatlands with pools in similar and different geographical settings. We also recognize the importance of long-term C exchange studies as those have, in some cases, shown significant inter-annual variability in NEE-CO_2 (e.g., Roulet *et al* 2007), and in others shown comparatively little (e.g., Nilsson *et al* 2008). One season of measurements can say nothing about interannual variability but the study period was warmer than the climate normal, which would suggest if anything that the heterotrophic respiration might have been greater than the longer term average suggesting that our conclusions are robust. At this point, our results suggest that generalized model parameterizations based on peatlands without pools may work until higher resolution models are possible. Understanding peatland open-water pools development is an active research area and studies have shown that the coverage by pools and their configuration are a function of topographic and geologic setting as well as developmental stage of the peatland (Foster and Glaser 1986, Foster and Wright 1990, Eppinga *et al* 2009, Morris *et al* 2013). Our results raise the question as to how the variation in pool proportion between peatlands affects the C exchange. These results also warrant further study to include methane and DOC losses to establish a complete NECB for peatland with pools; based on measurements from peatland without pools, these components should account for only 20–40% of the NEE-CO_2 uptake (Roulet *et al* 2007, Nilsson *et al* 2008).

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