Environmental Research Letters

LETTER

Can boreal peatlands with pools be net sinks for CO₂?

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Keywords: peatlands, open-water pools, carbon dioxide, net ecosystem exchange

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-CO₂) 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-CO₂ 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 CO₂ uptake during day and the autotrophic component of ecosystem respiration. The low CO₂ uptake combined with reduced CO₂ loss resulted in the site being a net sink for CO₂ 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 g C 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 CO₂, 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 g C 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 (Glasper 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 over-estimation 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 Tönnisson 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., Wanía 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-CO₂) 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-CO₂ 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 CO₂ from pools (e.g., Waddington and Roulet 2000, Pelletier et al 2014) and the NEE-CO₂ uptake for vegetated peat surfaces (e.g., Lafleur et al 2003, Sagerfors et al 2008), we hypothesize that peatlands with pools are either NEE-CO₂ neutral or a smaller sink for CO₂ during the growing than peatlands without pools. Here we present the results of one growing season (May–October) of NEE-CO₂ 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-CO₂ 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., Chamaedaphne 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 CO₂ 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 CO₂/H₂O 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 CO₂ fluxes were computed from the 10 Hz data using the EddyPro processing software (V5.1.0, LI-COR, Lincoln, NE). The CO₂ fluxes were derived from the covariance between vertical wind speed and CO₂ mixing ratio (Burba et al 2012). A two-dimensional coordinate rotation was applied. The EC CO₂ data were cleaned for quality flags output by the EddyPro processing software (Mauder and Foken 2004). The CO₂ data showing uptake at night were removed using a photo-synthetically active radiation (PAR) threshold of <20 μmol m⁻² s⁻¹ (Lafleur et al 2003). Following this step, the CO₂ 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-CO₂ were plotted (not shown) against friction velocity (u*), and a threshold
of 0.1 m s$^{-1}$ was used to identify insufficient turbulent mixing to assess reliable fluxes (e.g., Laflure 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$_{\text{max}}$ was evaluated by averaging the individual NEE-CO$_2$ measurements for PAR > 1000 μmol m$^{-2}$ 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$_2$ when PAR < 20 μmol m$^{-2}$ 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$_{\text{max}}$ (NEE-CO$_2$ when PAR > 1000 μmol m$^{-2}$ 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$_{\text{max}}$ increased from early to late growing season, reaching a maximum uptake of $-4.1 \mu$mol m$^{-2}$ 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$_2$ m$^{-2}$ 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$_2$ m$^{-2}$ 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
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
pools. We found that the monthly average diurnal trends in NEE-CO2 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 CO2 uptake is observed during the day and CO2 is released during the night (figure 3). The maximum photosynthetic uptake ($A_{\text{max}}$) calculated using a rectangular hyperbola relationship between GEP and PAR (see Frolking et al. 1998), and the ER calculated for an air...
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 ($R_{10} = 1.01 \mu\text{mol m}^{-2} \text{s}^{-1}$) (Olefeldt et al 2012) that is experiencing permafrost thaw and the Kaamanen subarctic mesotrophic fen ($R_{10} = 1.32 \mu\text{mol m}^{-2} \text{s}^{-1}$) (Lindroth et al 2007), which has ephemeral pools in the spring and early summer (Heikkilä 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 $A_{\text{max}}$ 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 ($-1.83 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$) is within the range of published mean daily NEE-CO$_2$ measured in pool-free peatlands ($-1.51$ to $-5.20 \text{ g CO}_2 \text{ m}^{-2} \text{ d}^{-1}$; 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 and 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

| Peatland site              | g CO$_2$ m$^{-2}$ d$^{-1}$ | Number of growing season | Source                  |
|---------------------------|---------------------------|---------------------------|-------------------------|
| Petite Rivière, Canada    | $-1.83$                   | 1                         | This study              |
| Mer Beue bog, Canada      | $-1.54$ to $-2.84$        | 4                         | Lefleur et al 2003      |
| Degero 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     |
sources of CO₂ to the atmosphere, the reduced ecosystem CO₂ uptake capacity is compensated by the limited CO₂ loss through respiration. This study is the first to present spatially integrated NEE-CO₂ 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-CO₂ (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-CO₂ uptake (Roulet et al 2007, Nilsson et al 2008).

Acknowledgments

The authors wish to acknowledge the financial support of the National Sciences and Engineering Research Council of Canada through an NSERC-CRD grant (90395670) to MG and a Discovery Grant (249846) to IBS. LP was funded through fellowships from NSERC PGSD3-388902-2010, the McConnell Foundation and the McGill Graduate Excellence Fellowship program. The authors would like to thank Dr Tim R Moore (McGill University); Dr Onil Bergeron; Dr Alain Tremblay and J-L Fréchette, (Hydro Quebec); and the field and lab assistance of H Asnong, A Lamalice, V Lefrançois, J Minville (UQAM); M Dalva, E Christiansen, S Crombie, C Lefrançois, C Watt, R Chen, F Ferber (McGill). The authors also thank A Baird for his insightful critical review, and A Laine (University of Helsinki) and K Dinsmore (CEH Edinburgh) for their clarification on NEE-CO₂ measurements from Glencar, Ireland and Cross Loughs South, Scotland. We also thank three anonymous reviewers for their comments and suggestions that helped improving the manuscript.

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