# Summertime greenhouse gas fluxes from an urban bog undergoing restoration through rewetting

A. Christen[1,2], R.S. Jassal[2], T.A. Black[2], N.J. Grant[2],
I. Hawthorne[4], M.S. Johnson[3,4], S.-C. Lee[1] and M. Merkens[5]

[1] Department of Geography / Atmospheric Science Program, The University of British Columbia, Vancouver, Canada
[2] Faculty of Land and Food Systems, The University of British Columbia, Vancouver, Canada
[3] Institute of Resources, Environment and Sustainability, The University of British Columbia, Vancouver, Canada
[4] Department of Earth, Ocean and Atmospheric Sciences, The University of British Columbia, Vancouver, Canada
[5] Planning, Policy and Environment Department, Metro Vancouver, Vancouver, Canada

---

## SUMMARY

Rewetting can promote the ecological recovery of disturbed peatland ecosystems and may help to revert these ecosystems to carbon dioxide ($CO_2$) sinks. However, rewetting of disturbed peatlands can also cause substantial emissions of methane ($CH_4$) and possibly nitrous oxide ($N_2O$). This study quantified summertime emissions of the three major long-lived greenhouse gases (GHGs) $CO_2$, $CH_4$ and $N_2O$; from undisturbed, disturbed and rewetted soils in the Burns Bog Ecological Conservancy Area (BBECA), a 20 km$^2$ urban bog located in Delta, British Columbia, Canada. Four sites were chosen that represent different stages before or after ecological recovery in the BBECA: (i) a relatively undisturbed scrub pine / *Sphagnum* / low shrub ecosystem; (ii) a *Rhynchospora alba* / *Sphagnum* ecosystem that was disturbed by peat mining more than 65 years ago; (iii) a *R. alba* / *Dulichium arundinaceum* ecosystem that was disturbed by peat mining 50 years ago and rewetted five years ago; and (iv) a disturbed and rewetted surface with little vegetation cover that was cleared of vegetation 16 years ago and rewetted two years ago. The GHG fluxes from soils and ground vegetation were measured at all sites during June–August 2014, using a portable non-steady-state chamber system for $CO_2$ and syringe sampling and laboratory analysis for $CH_4$ and $N_2O$ fluxes. All four sites exhibited net GHG emissions into the atmosphere, dominated by $CH_4$, which contributed 81–98 % of net $CO_2$ equivalent ($CO_2$e) emissions. Overall, the median $CH_4$ flux for all measurements and sites was ~74 mg m$^{-2}$ day$^{-1}$ (~30–410 mg m$^{-2}$ day$^{-1}$, 25$^{th}$–75$^{th}$ percentiles). Fluxes in the rewetted (water-saturated) sedge ecosystem were highest, with a quarter of the values higher than 3,000 mg m$^{-2}$ day$^{-1}$ (median 78 mg m$^{-2}$ day$^{-1}$). Exchange of $CO_2$ due to photosynthesis and respiration was of secondary importance compared to soil $CH_4$ emissions. Continuous $CO_2$ flux measurements using the eddy covariance approach in the disturbed and rewetted *R. alba* / *Sphagnum* site showed that the entire ecosystem, which included tall vegetation, was a weak $CO_2$ sink during the summer (average summertime $CO_2$ uptake of 3.59 g $CO_2$ m$^{-2}$ day$^{-1}$). No significant emission or uptake of $N_2O$ was observed. The results showed that $CH_4$ emissions dominated the net GHG emissions in this disturbed bog at different stages of recovery.

**KEY WORDS:** Burns Bog, carbon dioxide, methane, nitrous oxide, wetland restoration

---

## INTRODUCTION

Peatlands contain the highest carbon (C) stock *per* unit land area of all terrestrial ecosystems, and globally store 600 Gt C (Yu *et al.* 2010), which is about 70 % of the C currently in the atmosphere (Ciais *et al.* 2013). In their pristine state, peatlands are weak carbon dioxide ($CO_2$) sinks that accumulate atmospheric $CO_2$ over long timeframes and sequester it in the form of peat in the catotelm, the permanently wet layer below the surface (e.g. Roulet *et al.* 2007, Peichl *et al.* 2014). In water-saturated peat, dead plant material decomposes very slowly because of oxygen limitation (Bleuten *et al.* 2006), associated low water temperatures (for peatlands located in temperate and boreal regions) and limited microbial populations (Mentzer *et al.* 2006). These conditions can also result in methanogenesis, the formation of methane ($CH_4$) in the water-saturated peat. Part of the $CH_4$ formed can be oxidised under aerobic conditions before reaching the surface. Formation and oxidation of $CH_4$ in the peat is highly heterogeneous due to microtopographical controls on soil environmental conditions, water table variations and plant


DOI: 10.19189/MaP.2015.OMB.207

communities (Dinsmore *et al*. 2009, Turetsky *et al*. 2014). The magnitude of $CH_4$ emissions to the atmosphere depends on the production and oxidation of $CH_4$ in the peat and the efficiency of the mechanisms that transport the $CH_4$ formed in lower layers of the peat to the atmosphere (Hendriks *et al*. 2010). $CH_4$ formed in the water-saturated layers of the peat can escape to the atmosphere through three different pathways: diffusion, ebullition and transport through plants. Previous studies have suggested that when vascular plants are present, transport *via* pressure differences and/or diffusion through plant tissues is important and can dominate the flux (e.g. Waddington *et al*. 1996). Ebullition (formation of bubbles) is the main process in the absence of vegetation under waterlogged conditions (Vasander & Kettunen 2006). Globally, $CH_4$ emissions from peatlands and other wetlands account for about 30 % of all current $CH_4$ emissions to the atmosphere (Ciais *et al*. 2013).

Globally, peatlands have been degraded by land conversion and peat mining (OECD 1996, UNDP *et al*. 2000). When water-saturated peatlands are drained, the organic C in the peat becomes available for oxidation by microbes (Waddington & Price 2000). Furthermore, the exposed peat is vulnerable to wind erosion (Rochefort & Lode 2006) and can be lost through various pathways, for example as dissolved organic carbon (DOC), particulate organic carbon (POC) and through fires. The decomposed organic matter of a peatland under degradation will eventually enter the atmosphere in the form of $CO_2$ or $CH_4$. Drained peatlands are a significant source of $CO_2$ (IPCC 2014) and it is estimated that this process currently accounts for about 6 % of all global anthropogenic emissions of $CO_2$ (Joosten 2013). Therefore, protecting and maintaining peatlands in a pristine state will ensure that C stored in the peat remains sequestered and will mitigate further emissions.

Recently, emphasis has been placed on restoring drained and disturbed peatlands to conserve C and the unique regional ecosystem services of peatlands. It is critical to understand how the process of restoration will change greenhouse gas (GHG) exchange between peatlands and the atmosphere. Restoration efforts can revert the strong net sources of $CO_2$ of disturbed peatlands back into net sinks of $CO_2$ (e.g. Tuittila *et al*. 1999, Kivimäki *et al*. 2008, Strack *et al*. 2014). However, selected studies have shown that deliberate rewetting of disturbed peatlands to re-establish pre-disturbance ecosystem functioning can cause high to extreme emissions of $CH_4$ (e.g. Mahmood & Strack 2011, Knox *et al*. 2015). Restoration can also increase emissions of nitrous oxide ($N_2O$) if the previous disturbance involved agricultural activities (Kroon *et al*. 2010). Increased $CH_4$ emissions related to peatland restoration may be transient, and long-term C sequestration benefits are realised only when peatlands return to a more natural state and re-enter a mode of sequestering atmospheric C (Strack & Waddington 2012). Knowledge of the pathway of GHG emissions of rewetted peatlands is necessary to help identify GHG emission mitigation strategies in restoration management, and to inform effective C sequestration strategies in combination with efforts to accelerate ecological recovery. Because the ecological recovery and emission pathways depend not only on past and current management of the peatland, but also on the specific climate and geographical context (IPCC 2014), data from rewetted peatlands in different world regions is required in order to identify differences or commonalities and make more general recommendations. Currently, little is known about GHG emission dynamics following restoration and rewetting of disturbed peatlands and bogs on the west coast of Canada, which experiences a marine West Coast climate with dry summers and wet winters. Moreover, peatlands in urban settings have not yet been studied. This study reports summertime measurements of GHG emissions using chamber and eddy covariance techniques in a semi-urban bog under restoration in Metro Vancouver, a metropolitan area of 2.5 million inhabitants on the Pacific coast of Canada. The objective of this study was to determine the range and frequency distribution of summertime soil GHG fluxes at four sites that represent different stages of recovery after disturbance in the Burns Bog Ecological Conservancy Area (BBECA) located in Delta, British Columbia (122° 59' 05.87" W, 49° 07' 47.20" N). The summertime period was chosen because substantial emissions of $CH_4$ and $N_2O$ and high rates of exchange of $CO_2$ by photosynthesis and respiration were expected to occur at this time, due to high soil and air temperatures and high solar irradiance.

## MATERIALS AND METHODS

### Study area

The Burns Bog Ecological Conservancy Area (BBECA) is part of a remnant ombrotrophic raised bog ecosystem which is recognised as the largest expanse of undeveloped peatland within an urban metropolitan area in western Canada. The BBECA is also influenced by the nearby marine environment. It is located on the large estuarine delta of the Fraser River, which facilitates a distinct biogeochemistry, flora and fauna (Hebda *et al.* 2000, McDade 2000) and supports distinctive vegetation communities and recognised rare and endangered plant and wildlife species. While not pristine, the BBECA has retained enough of its ecological integrity to permit its restoration over time. The bog covered approximately 48 km$^2$ prior to the late 1800s. The encroachment of agriculture, industrial land use, numerous landfills and the development of transportation and utility corridors in the early 1900s altered and isolated approximately 40 % of the bog. The hydrology and ecology of the remaining contiguous bog have been further disrupted by marginal and internal ditching, peat extraction and related activities, as well as by shifts in land use on neighbouring properties towards peri-urban agriculture, infrastructure (landfills, highways) and settlements. In 2004 the federal, provincial, regional and municipal governments purchased a large portion (approximately 20 km$^2$) of the remaining undeveloped bog to establish the BBECA. The BBECA contains 14 km$^2$ of disturbed wetland ecosystems that were previously used for peat mining, agriculture or recreation; and about 6 km$^2$ of relatively undisturbed raised peat bog (Metro Vancouver 2007). The primary land management objective for the BBECA is the support of ecological recovery through restoration, conservation and protection as a raised bog ecosystem. This is achieved by a large-scale ditch blocking programme, which aims to retain and store rainwater within the raised bog area through the installation of dams and weirs within historic drainage ditches (Howie *et al.* 2009), and thus to limit water table fluctuations.

The BBECA contains widespread peatland vegetation communities dominated by *Sphagnum* mosses and plants belonging to the heather family (*Ericaceae*). Twenty-four ecosystem types have been identified, mapped and described for the BBECA using terrestrial ecosystem mapping methodologies (Resources Inventory Committee 1998). Extensive white beakrush (*Rhynchospora alba*) - *Sphagnum* meadows covered 56 % of the bog area at the time of classification (Madrone Consultants Ltd. 1999). Dominated by a near-complete cover of *Sphagnum* carpets, these meadows have noticeable, yet minor, components of tawny cottongrass (*Eriophorum virginicum*), sundew (*Drosera rotundifolia*) and false asphodel (*Tolfieldia glutinosa*). Scattered scrub pine (*Pinus contorta* var. *contorta*) and Labrador tea (*Ledum groenlandicum*) dot the landscape and bog cranberry (*Oxycoccus palustris*) trails over the *Sphagnum* carpets. Bog blueberry (*Vaccinium uliginosum*) is also common across these meadows.

**Measurement sites**

Five different sampling sites were chosen for GHG flux measurements. Four sites represent different stages of the typical ecological recovery after disturbance and were selected for closed chamber measurements of GHG exchange (Figure 1). A fifth site in a rewetted ecosystem was selected for a weather station / eddy covariance (EC) tower.

*“Undisturbed” (shrub -* Sphagnum*) site*

This site is relatively undisturbed, and consists of a scrub pine / *Sphagnum* / low shrub ecosystem that was never cleared of vegetation for peat extraction purposes or for agriculture (Table 1, Figure 1a). However, it is possible that it was compromised by changes in the water table for some period of time prior to establishment of the BBECA. The undisturbed site is characterised by scattered stunted scrub pine over a carpet of *Sphagnum* with a peat depth of 4.5 m. Hollows and hummocks of *Sphagnum tenellum* and *S. capillifolium* mixed with ericaceous shrub species and patches of maritime reindeer lichen (*Cladina portentosa* (Dufour) Follmann) provide nearly complete cover. In 2014, water table depth at this site ranged between 0.01 m during most of the winter months and 0.50 m in early September, and the average annual water table depth was 0.13 m.

*“Disturbed sedge -* Sphagnum*” site*

The disturbed sedge - *Sphagnum* site was subject to peat mining between 1930 and 1948. Peat was extracted from this area using the Atkins-Durbrow Hydropeat method (Göttlich *et al.* 1993), which involved cutting down trees and blasting the peat surface with pressurised water to dislodge peat from exposed tree roots. The site has a peat depth of ~4 m (Biggs 1976) and is characterised by widely spaced *Sphagnum* hummocks, usually associated with common bog shrub species, separated by large sparsely vegetated depressed areas which are often inundated with water for extended periods (Table 1, Figure 1b). White beakrush is common and a few stunted scrub pine trees are present. Continuous water level measurements are not available for this site. On the basis of manual observations, we estimate that the water table is between 0.25 m depth and the surface for most of the year.

*“Rewetted sedge” site*

The rewetted sedge site was subject to peat mining in the 1960s and was rewetted in 2008/2009. Peat was extracted using the Atkins-Durbrow Hydropeat method between 1963 and 1966. The elevated baulks

**(a)** Undisturbed **(b)** Disturbed sedge-*Sphagnum* **(c)** Rewetted sedge **(d)** Rewetted cleared

Figure 1. Photographs of the four chamber measurement sites in June 2014.

between the rectangular fields created by peat excavation are covered by scrub pine-*Sphagnum* heath, which in many cases grows on an undisturbed surface. The vegetation of the rewetted sedge site is characterised primarily by white beakrush and three-way sedge (*Dulichium arundinaceum*). Vegetation cover is incomplete and large patches of algae have developed in some of the shallow pools (Table 1, Figure 1c). Scattered bog shrubs including Labrador tea, bog blueberry and sweet gale (*Myrica gale*) exist mainly on drier hummocks, and *Sphagnum* cushions are found within the shrub hummocks. Peat depth is 5 m. This site is noticeably wetter than all the other study sites, with the water table remaining above the surface for much of the year. The average annual water level in 2014 was 0.08 m above the surface (maximum 0.14 m above the surface in winter and minimum 0.15 m below the surface in early September). Blocked ditches (2007/2008) adjacent to the site contribute to the wetting of the area.

*"Rewetted cleared" site*

The rewetted cleared site was cleared for commercial cranberry cultivation in 1998 and rewetted in 2012. Clearing involved the removal of existing vegetation and establishment of a uniform, level field of exposed catotelm peat (Table 1, Figure 1d). However, the commercial cranberry was never planted, and the site was naturally recolonised by the surrounding plant communities after abandonment. This area remained largely bare of vegetation until 2010 and was rewetted in 2012. Since then, it has developed a relatively sparse vegetation cover consisting primarily of low-growing Labrador tea patches, widely spaced birch (*Betula pendula*) trees and commercial blueberry (*Vaccinium corymbosum*) bushes (through natural colonisation), as well as scattered herb and other shrub species characteristic of bog ecosystems. *Sphagnum* occurs as very small hummocks of *S. capillifolium*, often associated with Labrador tea patches, and its cover is limited (visual

Table 1. Summary of all the measurement sites, their ecosystem characteristics, historical disturbances, locations and measurements.

| | Not restored | | Restored | | |
|---|---|---|---|---|---|
| **Site** | **Undisturbed shrub - *Sphagnum*** | **Disturbed sedge - *Sphagnum*** | **Rewetted sedge** | **Rewetted cleared** | **Rewetted sedge - *Sphagnum*** |
| **Location** (WGS-84) | 123°01'02.96"W 49°06'34.01"N | 122°59'47.76"W 49°07'09.37"N | 123°00'01.42"W 49°07'08.80"N | 123°00'02.97"W 49°06'37.20"N | 122°59'05.87"W 49°07'47.20"N |
| **Ecosystem type and classification** (2014) | Scrub pine / *Sphagnum* / low shrub (PSLS) | White beakrush / *Sphagnum* (BS) | White beakrush / three-way sedge (BTS) | Disturbed, mostly bare soil (DS) | White beakrush / *Sphagnum* (BS) |
| **Historical disturbances** | Possible lowering of water table | Peat extraction and lowering of water table | Peat extraction and lowering of water table | Cleared bog and lowering of water table | Peat extraction and lowering of water table |
| **Peat extraction method** | N/A | Atkins-Durbrow Hydropeat | Atkins-Durbrow Hydropeat | N/A | Atkins-Durbrow Hydropeat |
| **Period of disturbance** | Started 1930s | 1948 or before (> 66 years ago) | 1963–1966 (48 years ago) | 1998 (16 years ago) | 1957–1963 (51 years ago) |
| **Closest dam to rewet ecosystem** (year of installation) | none | none | 2008, 2009 (5 years ago) | 2012 (2 years ago) | 2008 (6 years ago) |
| **Greenhouse gas measurements** | Steady-state chamber measurements of $CO_2$ (8 collars per site), $CH_4$ and $N_2O$ (5 collars per site) | | | | Eddy covariance fluxes of $CO_2$ |
| **Climate measurements** | Soil temperature (2 replications) Soil volumetric water content (2 replications) | | | | Short wave irradiance, wind, precipitation |

(a) According to the ecosystem map of the BBECA.

estimate < 2 %). Peat depth is about 5.6 m. The water table at this site is close to or above the surface for most of the year, although surface cracking of the peat can be seen in mid-summer. In 2014 the water table fluctuated between a maximum depth of 0.26 m in late August and 0.14 m of standing water above the surface in November, and average annual water table depth was 0.02 m.

*"Rewetted sedge*-Sphagnum*" site with an eddy covariance flux tower*

An additional measurement site was established in the central part of the BBECA, in a disturbed and rewetted sedge-*Sphagnum* ecosystem characterised by white beakrush and *Sphagnum* but without any stunted scrub pine (Table 1). This site was chosen, as an area of suitably flat and homogeneous terrain, for establishment of a weather station / eddy covariance (EC) tower. The tower is located less than 50 m from the northern edge of a relatively homogeneous sedge -*Sphagnum* field (size: 400 m in the east–west direction and 150–300 m in the north–south direction) without any tall trees. This site was severely disturbed by peat extraction between 1957 and 1963. It was rewetted in 2008, with several weirs being used to block nearby ditches. Over the year (2014), the position of the water table ranged from 0.10 m below the surface (late summer, with visible small open-water ponds) to 0.03 m above the bog surface (flooded, winter). The peat depth is 5.9 m.

**Measurement procedures**

Five large circular collars (0.21 m internal diameter, 0.0692 m$^2$ surface area) and eight small circular collars (0.10 m inner diameter, 0.0157 $m^2$ surface area) were permanently installed in each of the four chamber sites. The small collars were used to measure soil $CO_2$ fluxes using a portable non-steady-state chamber system with a portable infrared gas analyser (Jassal *et al.* 2005, 2007). The large collars were used to measure soil $CH_4$ and $N_2O$ fluxes by manually taking gas samples with a syringe, followed by laboratory analysis by gas chromatography as in Jassal *et al.* (2008). The measurement of soil $CH_4$ and $N_2O$ concentrations with signal-to-noise ratios sufficient to detect fluxes with reasonable accuracy required a larger collar area to height ratio. Collar locations were chosen to represent different environmental conditions with respect to water content, microtopography, vegetation cover and proximity to trees. Soil cover within the collars included small ground vegetation or grasses but no shrubs, taller grasses or trees. Approximately half of the collars *per* site were installed on hummocks and in generally drier areas (where applicable), while the remainder were installed in wet areas (hollows). The collars were installed to minimally disturb the soil and the vegetation inside the collars, although in many cases installation required cutting (with a sharp knife) of roots or *Sphagnum* down to 0.05 m depth. The height of each small collar (for $CO_2$) was 0.04 m above the local surface. The heights of the large collars (for $CH_4$ and $N_2O$) were adjusted to account for the varying height of vegetation, and ranged between 0.08 and 0.17 m (resulting in chamber volumes between 0.0055 and 0.0118 $m^3$). All collars were installed in early to mid-June 2014, 3–4 weeks before the first flux measurements took place, to allow for soil settling and some vegetation regrowth. During sampling, traffic near the collars was restricted and boardwalks were installed in selected areas with wet soils.

*Chamber measurements of soil $CO_2$ flux*

Soil $CO_2$ fluxes were measured using opaque (PVC) and transparent (acrylic) chambers, depending on whether respiration (opaque chambers) or net ecosystem exchange (NEE, i.e. ecosystem respiration minus gross ecosystem photosynthesis) (transparent chambers) was of interest. The chamber was placed on each small collar for a two-minute period. A foam gasket provided a seal between the collar and the chamber (geometric volume $V$ = 0.001426 $m^3$). A pump (flow rate of 0.0006 $m^3$ $min^{-1}$) circulated air from the chamber into a portable battery-operated infrared gas analyser (IRGA) (LI-800, LI-COR Inc., Lincoln, NE, USA, operated at 1 Hz) and back into the chamber through a closed circuit. The IRGA measured $CO_2$ (ppmv) and water vapour concentrations at one-second intervals during the run. The data from the IRGA were digitised using a 21X data logger (Campbell Scientific Inc., Logan, UT, USA) and stored for later calculation of the rate of change in $CO_2$ mixing ratios in the chamber over the period of measurement (see below). Simultaneously, a thermocouple probe (SMP-NP-E-125G-6, Type E, Omega Environmental, Laval, QC, Canada) was used to measure soil temperature at ~0.05-m depth just outside the collar. The IRGA was calibrated using a two-point calibration in the laboratory using zero (pure dry $N_2$) and 414.07 ppmv $CO_2$ gas (in dry air).

For measurements with the transparent chamber, a quantum sensor (LI-190, LI-COR Inc., Lincoln, NE) measured photosynthetic photon flux density (PPFD in μmol $m^{-2}$ $s^{-1}$) during the period of each measurement. Transparent chamber measurements were repeated four times in a sequence for the same collar to obtain light response curves. This involved progressively covering the chamber (and the quantum sensor) with cloth sheets of decreasing transparency using the shade-cloth methodology (e.g. Marini & Sowers 1990, Riutta *et al*. 2007); 100 % transparency (i.e. full ambient sunlight), 39.4 % transparency, 10.8 % transparency and 0 % transparency (completely dark) cloth sheets were mounted successively over the chamber to produce different PPFD levels. These measurements were completed within 20 minutes to avoid substantial changes in solar altitude, incoming PPFD and other environmental controls.

*Chamber measurements of soil $CH_4$ and $N_2O$ fluxes*

$CH_4$ and $N_2O$ fluxes were measured over a period of 30 minutes following a procedure similar to that described by Jassal *et al.* (2011). During the sampling period, the collars were covered with a transparent acrylic lid equipped with a foam gasket and a battery-operated fan that ensured mixing within the chamber headspace. Five 20 ml samples of the chamber headspace air were manually extracted with a syringe at 0, 5, 10, 20 and 30 minutes after chamber deployment, and were immediately transferred into evacuated 12 ml vials (Exetainers®, Labco Ltd., Buckinghamshire, UK). All vials were stored and transported in a cooled box and, on the same day, transferred to a temperature-controlled cooled storage room. The vials were stored upside down in water to prevent any leakage before analysis in the laboratory. The analysis of $CH_4$ and $N_2O$ in the vials was performed using an Agilent 7890A (G3440A, Agilent Technologies, Santa Clara, California, USA) gas chromatography (GC) system. Samples were injected by a Combi-Pal autosampler (CTC Analytics, Zwingen, Switzerland), drawn from the vials using a 2.5 ml $N_2$ purged glass syringe with a HD-Type PTFE tipped syringe plunger and 23-gauge needle (CTC Analytics AG, Zwingen, Switzerland), and injected into the GC stainless steel, heated (110 ºC) purged-packed inlet using $N_2$ (99.999 %) as carrier gas. Gases were detected with a flame ionisation detector (FID, 250 ºC, for $CH_4$) and a micro-electron capture detector (µECD, 300 ºC, for $N_2O$).

*EC measurements of ecosystem $CO_2$ exchange*

Ecosystem fluxes of $CO_2$ were measured using an eddy covariance (EC) system mounted on a micrometeorological tower at the rewetted sedge - *Sphagnum* site. The EC system consisted of an ultrasonic anemometer-thermometer (CSAT-3, Campbell Scientific Inc., Logan, UT) and a $H_2O/CO_2$ open-path infrared gas analyser (LI-7500, LI-COR Inc.), which were installed at a height of 1.8 m on a boom extending southwards from a scaffolding tower. The system measured vertical wind speed $w$ (m s$^{-1}$) and $CO_2$ molar density $\rho_c$ (mmol m$^{-3}$) at 10 Hz. Data were sampled on a data logger (CR1000, Campbell Scientific Inc.). Prior to deployment, the LI-7500 was calibrated in the laboratory using a two-stage calibration process with $N_2$ for 0 ppm and a span gas (similar to calibration of the portable chamber system IRGA).

*Climate measurements*

A continuous time series of environmental variables used to model and extrapolate fluxes over the growing season was recorded at each site. The variables included soil temperature at 0.05 m depth, recorded with custom made Type T (copper-constantan) thermocouples, and soil water content recorded with CS616 (Campbell Scientific Inc.) sensors installed vertically to integrate volumetric soil water content from the surface to 0.30 m depth at all four chamber sites and at the flux tower. All sites, with the exception of the disturbed sedge - *Sphagnum* site, were equipped with one or several dipwells that measured long-term (i.e. multi-year) changes in water table level (provided by the municipality of Delta, BC). At the flux tower, a four-component net radiometer (model CNR-1, Kipp & Zonen, Delft, Netherlands) provided continuous, unobstructed short wave irradiance $K_\downarrow$ (in W m$^{-2}$) during the study period. $K_\downarrow$ was used to model photosynthesis.

**Calculation of greenhouse gas fluxes**

*Calculation of soil $CO_2$ fluxes from chamber measurements*

Digital data from the portable chamber systems included $CO_2$ and water vapour concentrations, temperature and PPFD at 1 Hz. $CO_2$ concentrations were converted into mixing ratios ($m$) in µmol (mol dry air)$^{-1}$ and the rate of change in $m$ with time ($dm/dt$) was calculated using a linear regression over the two-minute period following chamber deployment. Data from the first 20 seconds of the run were discarded to avoid the effects of disturbance and pressure fluctuations during and shortly after chamber deployment. The soil $CO_2$ flux was then calculated using:

$$F_{CO_2} = \frac{\rho_a V_e}{A}\frac{dm}{dt} \qquad [1]$$

where $\rho_a$ is the dry air density, $A$ is the surface area (0.0157 m$^2$) and $V_e$ is the effective volume, which was assumed to be 1.1 times the geometric volume, $V$, of the chamber (Drewitt *et al.* 2002).

*Calculation of soil $CH_4$ and $N_2O$ fluxes from chamber measurements*

A similar procedure was used to calculate $N_2O$ and $CH_4$ fluxes from the five samples taken of mixing ratios of $CH_4$ and $N_2O$ in µmol (mol dry air)$^{-1}$ in the chamber headspace. In this case the area $A$ was 0.0692 m$^2$, but the geometric volume $V$ (m$^3$) was determined for each collar taken as $V = Ah$, where $h$ is the height of the collar above the soil surface (m).

For $N_2O$, a linear fit was used to determine $dm/dt$ from the five measurements over 30 minutes. However, for $CH_4$ nearly all of the runs increased non-linearly over the 30 minute period. Hence, an exponential function was fitted through the mixing ratio ($m$) values for $CH_4$ determined at 0, 5, 10, 20 and 30 minutes following Jassal *et al.* (2012) using a non-linear least squares fit.

$$m(t) = m_z - (m_z - m_0)\, \mathrm{e}^{-\alpha t} \qquad [2]$$

Here, $t$ is the time (s) since the start of the chamber run, $m_0$ is the mixing ratio at $t$ = 0 before closing the chamber and $m_z$ is the theoretical upper limit of chamber headspace mixing ratio. $\alpha$ (s$^{-1}$) is an empirical parameter that describes the curvature and is the reciprocal of the chamber time constant (Jassal *et al.* 2012). $dm/dt$ was then calculated at $t$ = 0 using:

$$\left.\frac{dm}{dt}\right|_{t=0} = \alpha(m_z - m_0) \qquad [3]$$

and the flux in µmol m$^{-2}$ s$^{-1}$ was determined as in [1] for each collar, using relevant values of $V_e$. Several samples exhibited step changes in the chamber $CH_4$ concentration during the 30-minute measurement period. These step-changes could have been caused by ebullition emissions during sampling, enhanced due to pressure disturbances or from researchers' added weight on the soil surface near the collar. Hence, all runs with step changes in $m$ (13 out of 60) were discarded. A run was considered to be contaminated if $m$ did not increase monotonically over five samples, and simultaneously the difference between the largest and smallest concentrations in the five samples was larger than 0.1 ppm.

*Eddy covariance flux calculations for $CO_2$*

EC fluxes of $CO_2$ were calculated based on 10-Hz data of stored vertical wind speed and $CO_2$ molar density over blocks of 30 minutes for the period between 09 July and 11 August 2014. Before flux calculation, the co-ordinate system of wind components was corrected for tilt (double rotation, no detrending) (Rebmann *et al*. 2012). Fluxes were corrected for density effects due to sensible heat and water vapour transfer (Webb *et al.* 1980) and for high-frequency flux losses based on path averaging of the sensors (Moore 1986). Data processing and quality controls followed the procedures outlined in Crawford *et al.* (2009). Night-time ($K_{\downarrow}$ < 2 W $m^{-2}$) flux measurements when the friction velocity $u_*$ was less than a threshold value of 0.08 m $s^{-1}$ were not used and instead filled using the mean diurnal variation (MDV) approach (Falge *et al*. 2001) on an hourly resolution over the study period.

**Modelling fluxes**

For soil $CO_2$ fluxes, the strong diurnal variability due to environmental controls (i.e. PPFD and soil temperature) prevented a simple averaging of the daytime measurements. The $CO_2$ released from soil respiration and above-ground respiration of the small ground vegetation in the collars ($R$ in µmol $m^{-2}$ $s^{-1}$) and the $CO_2$ uptake due to gross photosynthesis ($P$ in µmol $m^{-2}$ $s^{-1}$) by the vegetation in the collars were modelled separately, and then aggregated into a summertime net $CO_2$ flux ($\tilde{F}_{CO2}$). For the fluxes of $CH_4$ and $N_2O$, averaged statistics were calculated *per* collar and *per* site without any temporal modelling.

*Modelling soil and ground-level vegetation respiration*

All $R$ values from a particular collar were plotted against simultaneously measured soil temperature, $T$. Although volumetric soil water content ($\theta_w$) can be another important control on $R$ in peatlands (Luo & Zhou 2006), it changed little over the study period within the 0–0.30 m layer, except at the undisturbed site. For simplicity and due to the small range of $\theta_w$, $R$ was modelled only as a function of $T$. All $R$ measurements at each collar were used to fit an empirical temperature-dependency curve based on the work of Lloyd & Taylor (1994):

$$R = R_{ref}\ \exp\left[E\left(\frac{1}{T_{\mathrm{ref}} - T_0} - \frac{1}{T - T_0}\right)\right] \qquad [4]$$

where $T$ is the soil temperature (K) at 0.05 m depth, $T_{ref}$ is the reference temperature set to 293.15 K (20 ºC), and $T_0$ is the temperature at which all respiration ceases (set to 227.13 K). $R_{ref}$ is the reference respiration (µmol $m^{-2}$ $s^{-1}$) at $T = T_{ref}$. Using a gradient-expansion algorithm to compute a non-linear least squares fit, $R_{ref}$ and the empirical parameter $E$ were determined for each collar. While $R_{ref}$ was not constrained, $E$ was allowed to vary only within the range 150–600 K. Values of $R_{ref}$ and $E$ for individual collars were then used to extrapolate $R\ (t,c)$ based on Equation [4] for each time step ($t$) of ten minutes and collar number ($c$) using the continuously measured soil temperatures $T$ at each site. The study period average $\tilde{R}$ at a site was then calculated as averaged $R$ over all $N$ time steps and all eight collars at each site:

$$\tilde{R} = \frac{1}{8N}\sum_{t=1}^{N}\sum_{c=1}^{8} R(c,t) \qquad [5]$$

where $N$ is the number of time steps in the study period.

*Modelling ground-level photosynthesis*

For each collar, two light response curves were determined using transparent chamber measurements at four different PPFD values made on two different days. For each light response curve, the rate of gross photosynthesis $P$ (µmol $m^{-2}$ $s^{-1}$) at a given PPFD was calculated as

$$P_{(\mathrm{PPFD})} = -\left(F_{\mathrm{CO_2}\ (\mathrm{PPFD})} - F_{\mathrm{CO_2}\ (\mathrm{PPFD=0})}\right) \qquad [6]$$

where $F_{\mathrm{CO_2}\ (\mathrm{PPFD})}$ is the measured flux of $CO_2$ at the given light level (PPFD), and $F_{\mathrm{CO_2}\ (\mathrm{PPFD=0})}$ is the measured flux of $CO_2$ with a completely dark cover (PPFD = 0 µmol $m^{-2}$ $s^{-1}$) for the same response curve. The minus sign is introduced to define $P_{(\mathrm{PPFD})}$ as positive for uptake of $CO_2$. If Equation [6] resulted in a negative $P_{(\mathrm{PPFD})}$, it was set to zero. For each light response curve, a non-rectangular hyperbolic function (Ögren & Evans 1993) was fitted through measured PPFD and the corresponding $P_{(\mathrm{PPFD})}$ obtained using Equation [6] as follows:

$$P_{(\mathrm{PPFD})} = \frac{\phi\ \mathrm{PPFD} + P_m - \sqrt{(\phi\ \mathrm{PPFD} + P_m)^2 - 4C\ \phi\ \mathrm{PPFD}\ P_m}}{2C} \quad [7]$$

where $P_m$ is the maximum $P$ at light saturation, $C$ is the curvature and $\phi$ is the maximum quantum yield. Using a non-linear least squares fit, $P_m$ was determined for each curve. The curvature was fixed at $C$ = 0.7 and the maximum quantum yield was determined to be 0.01 µmol mol$^{-1}$ based on EC measurements at the rewetted sedge - *Sphagnum* site. For each collar, the two retrieved $P_m$ values from the two different dates were averaged to obtain a single $P_m$ for each collar.

To model $P$ for each collar and time step over the entire study period (26 June to 11 August 2014), a continuous time series of half-hourly PPFD values was firstly constructed. We assumed that changes in $\theta_w$ and air and soil temperature had little effect on $P$ over the study period. Continuous PPFD data were determined from $K_\downarrow$ measured at the flux tower using PPFD $= j\ K_\downarrow$, where $j$ = 2.01 mol J$^{-1}$ (Crawford & Christen 2015). For time steps when no measurements of $K_\downarrow$ were available at the flux tower, $K_\downarrow$ for a station 12 km north of the BBECA on a tower in the City of Vancouver (Vancouver-Sunset, 49°13' 34.0" N, 123°04'42.2" W) was used instead. The study period average $\tilde{P}$ for a site was then calculated as the averaged $P$ over all time steps and all collars using an equation similar to Equation [5], but replacing $R$ by $P$. Study-period averaged $\tilde{F}_{CO2}$ (µmol m$^{-2}$ s$^{-1}$) was calculated for each site as:

$$\tilde{F}_{CO2} = \tilde{R} - \tilde{P} \quad [8]$$

*Ecosystem respiration and gross ecosystem photosynthesis*

Net flux, $\tilde{F}_{CO2}$ measured in the collars at the four sites of the sequence represents the soil and ground-level plant respiration ($R$) and photosynthesis ($P$) of ground-level plants. In contrast, fluxes measured by EC at the flux tower quantify net ecosystem exchange (NEE) or net ecosystem productivity (NEP = - NEE) integrated over the footprint including tall vegetation (grasses, shrubs). NEE was partitioned into gross ecosystem photosynthesis (GEP) and ecosystem respiration ($R_e$) using night-time EC measurements of NEE. GEP was calculated by subtracting daytime NEE from $R_e$. Unlike soil and ground-level plant $R$, $R_e$ also includes autotrophic respiration of taller grasses and shrubs.

*Calculating net GHG flux in terms of $CO_2$ equivalent mass flux ($F_{CO_2e}$)*

We compared the net GHG fluxes at the four sites by considering the GHG warming potential (GWP) for each gas after converting their molar fluxes into $CO_2$ equivalent mass fluxes as follows:

$$F_{\mathrm{CO_2e}}(s) = \mathrm{GWP}_s\ m_s\ \tilde{F}_s \quad [9]$$

where $F_{\mathrm{CO_2e}}$ (s) is the equivalent mass flux of the gas species ($CO_2$, $CH_4$ or $N_2O$) expressed in g $CO_2$e m$^{-2}$ day$^{-1}$, $\tilde{F}_s$ is the study-period averaged molar flux *per* site converted to mol m$^{-2}$ day$^{-1}$ for the species, $m_s$ is its molar mass (g mol$^{-1}$), and $\mathrm{GWP}_s$ is the mass-based GWP (g g$^{-1}$). We used the 100-yr GWPs for $CO_2$, $CH_4$ and $N_2O$ of 1, 28 and 265, respectively (Myhre *et al.* 2013). The total $CO_2$e emissions from soils at a particular site were then calculated as the sum of the $\mathrm{CO_2e}$ (s) values for $CO_2$, $CH_4$ and $N_2O$:

$$F_{\mathrm{CO_2e}} = m_{CO2}\ \tilde{F}_{CO2} + 28\ m_{CH4}\tilde{F}_{CH4} + 265\ m_{N2O}\tilde{F}_{N2O} \quad [10]$$

$\tilde{F}_{CH4}$ and $\tilde{F}_{N2O}$ were calculated as the average of all individual measurements at all collars, and then averaged over all collars at a site. $\tilde{F}_{CO2}$ was calculated using Equation [8].

## RESULTS

### Climate conditions

The study period (26 June to 11 August 2014) was characterised by generally dry weather with clear sky conditions on 27 days and high $K_\downarrow$, on average 23.24 MJ m$^{-2}$ day$^{-1}$. Precipitation occurred on only eight days during this period and totalled 22.2 mm (Figure 2). Mean air temperature was 18.2 ºC. Values of $\theta_w$ were high (Table 2) and the water table at all the sites was shallowest at the beginning of the period (not shown). Over the study period, the highest values of $\theta_w$ were measured at the rewetted sedge site, followed by the rewetted cleared and undisturbed sites, and the lowest values at the disturbed sedge - *Sphagnum* site (Table 2). Water table depth increased


 DOI: 10.19189/MaP.2015.OMB.207

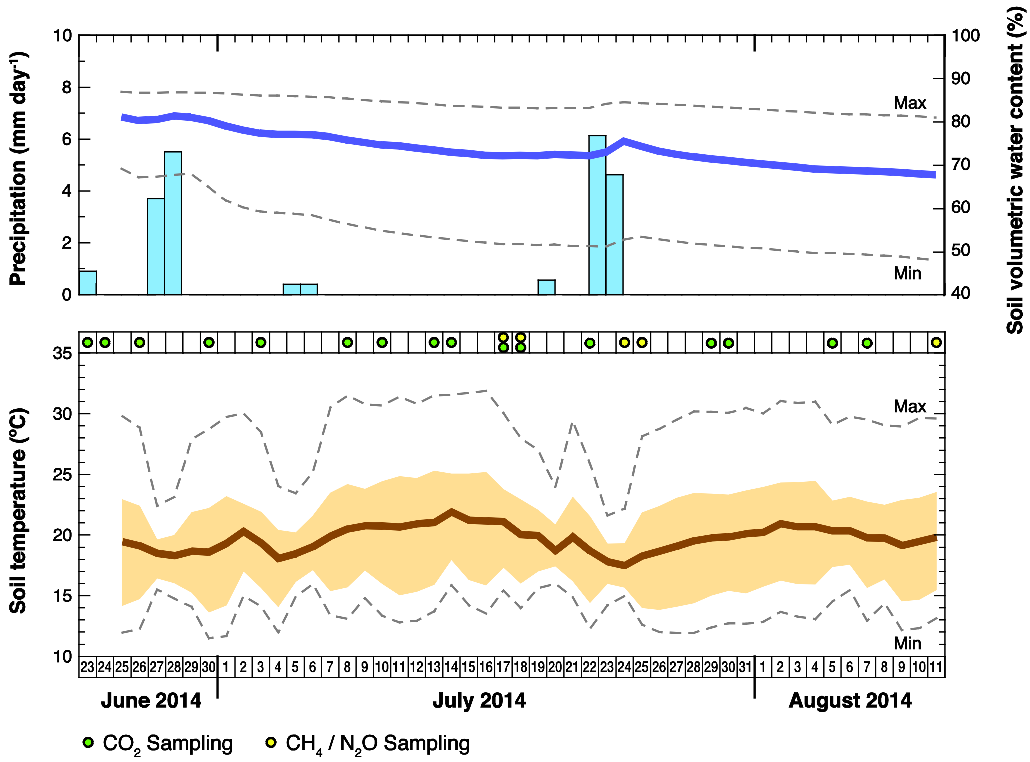


Figure 2. Precipitation and volumetric water content of soil (top panel) and soil temperature (bottom panel) over the period of greenhouse gas (GHG) flux measurements in summer 2014. The green and yellow dots indicate dates when manual soil GHG flux measurements were made to determine carbon dioxide ($CO_2$), methane ($CH_4$) and/or nitrous oxide ($N_2O$) fluxes. Soil temperature and soil volumetric water content are ensemble averages for all four sites of the sequence (two replications at each site). For soil temperature, the shaded region shows the daily maximum and minimum of the ensemble soil temperature. The dotted line shows the maximum and minimum of all eight measurements on each day. Precipitation is a composite series between the Environment Canada Climate Station "Delta Burns Bog" and the measurements from the flux tower after 09 July 2014, both located within the BBECA.

Table 2. Water table depth, soil water content and soil temperature at the four chamber measurement sites during the measurement period (26 June to 11 August, 2014).

| | **Not restored** | | **Restored** | |
|---|---|---|---|---|
| **Site** | **Undisturbed shrub - *Sphagnum*** | **Disturbed sedge - *Sphagnum*** | **Rewetted sedge** | **Rewetted cleared** |
| Average (and range) of **water table depth** [(a)] | 0.22 m (0.14 to 0.31) | ~0.25 m (N/A) | 0.03 m (-0.02 to 0.12 m) | 0.16 m (0.09 to 0.25 m) |
| Average (and range) of **soil volumetric water content** (0–0.30 m) [(b)] | 72 % (64–81 %) | Hollows: 84 % (80–87 %) Hummock: 55 % (48–69 %) | 78 % (75–85 %) | 75 % (61–86 %) |
| Average (and range) of **soil temperature** [(c)] | 18.5 °C (12.9—24.9 °C) | 17.8 °C (11.8–22.8 °C) | 20.2 °C (13.1–25.9 °C) | 21.5 °C (14.4–28.3 °C) |

[(a)] Depth of water table below surface measured by piezometers, negative values denote standing water above surface.
[(b)] Integrated measurement over top 0.30 m using two TDR probes. All sites except the disturbed sedge - *Sphagnum* site report the average of the two probes. At the disturbed sedge - *Sphagnum* site, the distinct microtopography causes two water content régimes.
[(c)] Averaged over two soil thermocouples installed at 0.05 m depth.

(not shown) and $\theta_w$ decreased towards the end of the study period (Figure 2). The highest spatial differentiation between drier micro-environments (e.g. hummocks) and wet micro-environments in local depressions (hollows) was at the disturbed (but not rewetted) sedge - *Sphagnum* site. Most collars at the rewetted sedge site remained water-saturated over the entire study period, whereas many collars at the rewetted cleared and undisturbed sites developed shallow dry surface layers.

Average soil temperature, $T$ at the 0.05-m depth, ranged between 17.8 and 21.5 ºC depending on the site (Table 2). The highest average $T$ was measured at the rewetted cleared site, probably due to the low albedo of the dark exposed bare soil and the lack of shading vegetation. The lowest average $T$ of 17.8 ºC was recorded at the densely vegetated disturbed sedge - *Sphagnum* site.

### Carbon dioxide fluxes

*Respiration of the soil and ground-level vegetation*

Respiration ($R$) determined in the chambers ranged between close to zero and 4.57 µmol m$^{-2}$ s$^{-1}$ ($n$ = 309 for all sites). Figure 3a shows the cumulative frequency distributions of all measured $R$ values sorted by site, and Figure 3b shows the same information as box plots. The two sites that have not been rewetted (undisturbed, disturbed sedge - *Sphagnum*) show similar distributions in the lower two quartiles but diverge in the upper two quartiles, whereas the undisturbed site shows a larger range and higher values for individual $R$ values. The measurements at the undisturbed site resulted in a median $R$ of 1.13 (mean: 1.33; max: 4.13) µmol m$^{-2}$ s$^{-1}$ and at the sedge - *Sphagnum* site in a median $R$ of 1.15 (mean: 1.06, max: 2.01) µmol m$^{-2}$ s$^{-1}$. In contrast, we found consistently lower $R$ at the rewetted sedge site across all four quartiles with a median $R$ of 0.63 (mean: 0.68, max: 2.10) µmol m$^{-2}$ s$^{-1}$. This was the site that experienced the lowest soil temperatures (17.9 ºC) and shallowest water table (Table 2). The rewetted cleared site (where the top soil dried over the summer) showed the highest median $R$ measurements with 1.39 (mean: 1.46, max: 4.57) µmol m$^{-2}$ s$^{-1}$. This was also the site with warmest average soil temperature over the study period (21.5 ºC). Figure 4 shows extrapolated values of $\tilde{R}$ over the entire period by site. Highest $\tilde{R}$ was found at the rewetted cleared site with 1.57 µmol m$^{-2}$ s$^{-1}$ (5.9 g $CO_2$ m$^{-2}$ day$^{-1}$), and the lowest $\tilde{R}$ at the most water saturated rewetted sedge site with 0.90 µmol m$^{-2}$ s$^{-1}$ (3.4 g $CO_2$ m$^{-2}$ day$^{-1}$). Variability between the eight collars at each site was large.

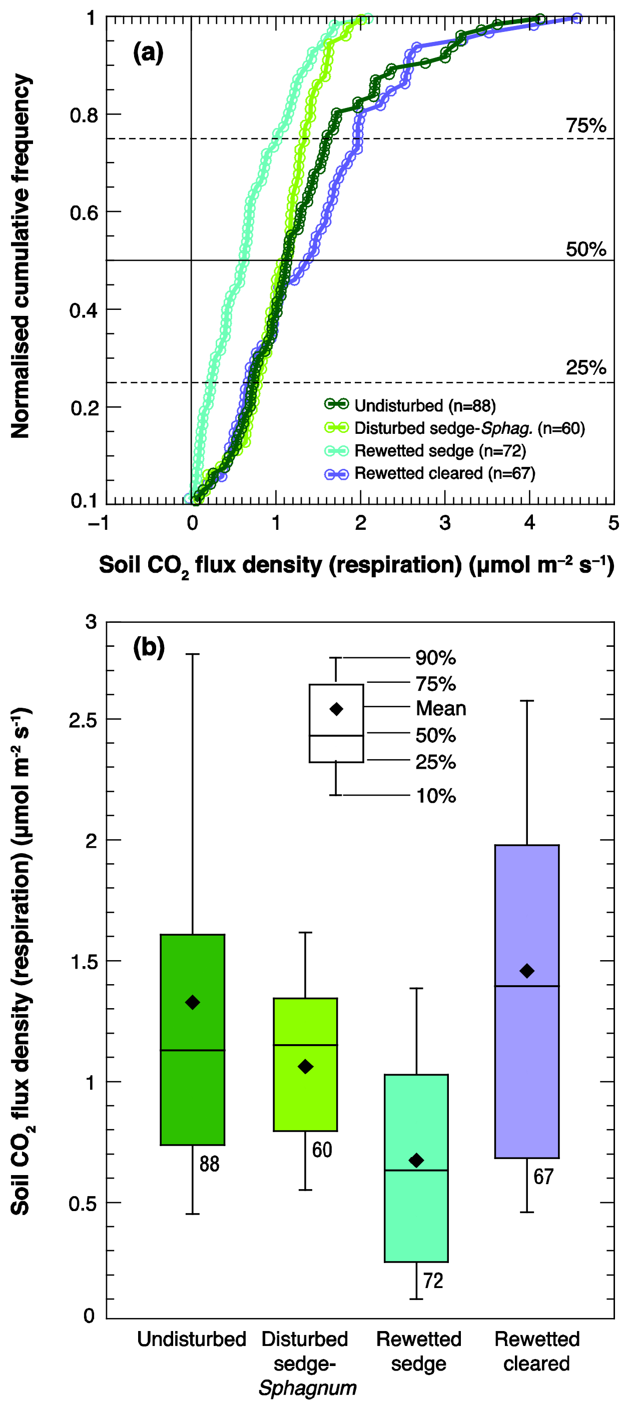


Figure 3. (a) Cumulative frequency distributions of all individual soil carbon dioxide ($CO_2$) flux measurements (µmol m$^{-2}$ s$^{-1}$) with an opaque chamber. Data from all sites and all collars represent soil respiration and autotrophic respiration of small plants within the collars, measured between 23 July and 07 August 2014; and (b) percentiles in the form of a boxplot. The number of measurements considered at each site is given in brackets (a) or below the boxes (b).

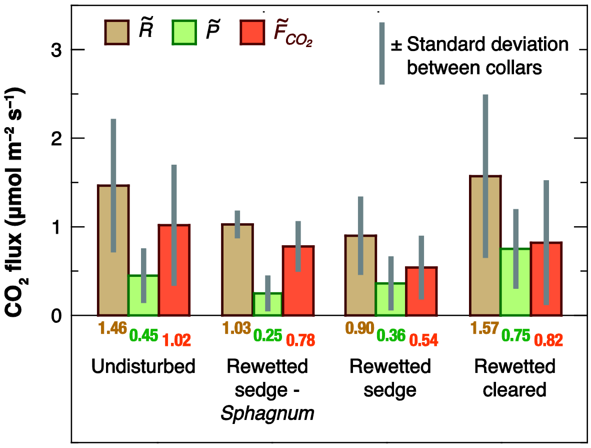


Figure 4. Calculated summertime net carbon dioxide ($CO_2$) flux from the ground and low-growing vegetation ($\tilde{F}_{CO2}$) separated into soil respiration plus above-ground autotrophic respiration of the vegetation in the collars ($\tilde{R}$) and photosynthesis of the vegetation in the collars ($\tilde{P}$) at all four sites for the period 26 Jun to 11 Aug 2014.

*Photosynthesis of the ground-level vegetation*

The highest photosynthesis ($P$) rates of the ground vegetation in the collars were observed at the rewetted cleared site and at the undisturbed site, in particular in collars with grassy and herbaceous vegetation. Collars with *Sphagnum* had generally lower $P$ values. $P$ determined from light response curves in the collars represents only the low ground vegetation (low sedges, herbs, woody scrub, *Sphagnum*) that grew within the collars. Figure 4 shows extrapolated values of $\tilde{P}$ over the entire period by site. The highest average $\tilde{P}$ value of 0.75 μmol $m^{-2}$ $s^{-1}$ (2.9 g $CO_2$ $m^{-2}$ $day^{-1}$) was extrapolated for the rewetted cleared site, and the lowest average $\tilde{P}$ value of 0.25 μmol $m^{-2}$ $s^{-1}$ (0.9 g $CO_2$ $m^{-2}$ $day^{-1}$) for the disturbed sedge - *Sphagnum* site.

*Net $CO_2$ exchange of soil and ground-level vegetation ($\tilde{F}_{CO2}$)*

Figure 4 shows $\tilde{F}_{CO2}$ averaged over the study period in relation to site-averaged $\tilde{R}$ and $\tilde{P}$ following Equation [8]. The positive values of $\tilde{F}_{CO2}$ indicate that the soil and low-growing vegetation at all four sites were sources of $CO_2$ during the study period. The highest $\tilde{F}_{CO2}$ value was found at the undisturbed site with 1.02 μmol $m^{-2}$ $s^{-1}$ (3.9 g $CO_2$ $m^{-2}$ $day^{-1}$), followed by the rewetted cleared site with 0.82 μmol $m^{-2}$ $s^{-1}$ (3.1 g $CO_2$ $m^{-2}$ $day^{-1}$) and then the disturbed sedge - *Sphagnum* site with 0.78 μmol $m^{-2}$ $s^{-1}$ (3.0 g $CO_2$ $m^{-2}$ $day^{-1}$). The lowest $\tilde{F}_{CO_2}$ value, found at the rewetted sedge site, was 0.54 μmol $m^{-2}$ $s^{-1}$ (2.0 g $CO_2$ $m^{-2}$ $day^{-1}$). The ratio of $P$ to $R$ increased with rewetting. The quotient $P/R$ was 0.24 at the disturbed sedge - *Sphagnum* site, 0.31 at the undisturbed site, 0.40 at the rewetted sedge site and 0.48 (highest) at the rewetted cleared site.

*Net ecosystem exchange (NEE)*

The above values of net $CO_2$ loss from the soil and ground-level vegetation ($\tilde{F}_{CO2}$) are in contrast to the EC-measured NEE of the flux tower footprint (Figure 5), where daily average NEE was -0.94 μmol $m^{-2}$ $s^{-1}$ or -3.59 g $CO_2$ $m^{-2}$ $day^{-1}$ over the study period, indicating that the entire ecosystem was a net $CO_2$ sink when the taller vegetation was taken into account. $R_e$ for the flux tower was estimated to be 1.36 μmol $m^{-2}$ $s^{-1}$ or 5.17 g $CO_2$ $m^{-2}$ $day^{-1}$, which, as expected, was higher (by ~20 %) than the all-site average of ground-level respiration, i.e. $\tilde{R}$ (1.13 μmol $m^{-2}$ $s^{-1}$) measured using the opaque chambers. Figure 6 shows the EC-derived GEP in the footprint of the flux tower plotted against PPFD. For PPFD > 169 μmol $m^{-2}$ $s^{-1}$, the ecosystem was a $CO_2$ sink when GEP > $R_e$. GEP at the flux tower was 2.30 μmol $m^{-2}$ $s^{-1}$ (8.76 g $CO_2$ $m^{-2}$ $day^{-1}$) for the study period.

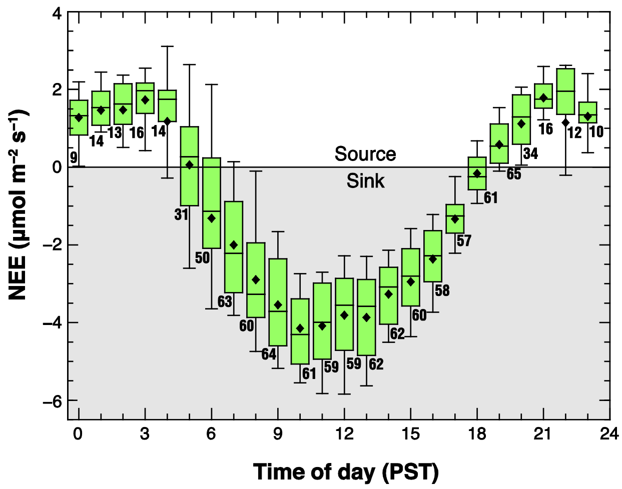


Figure 5. Ensemble-averaged diurnal course of eddy covariance (EC) measured net ecosystem exchange (NEE = ecosystem $CO_2$ flux) for the flux tower footprint between 09 July and 11 August 2014. The night-time $u_*$ threshold for data to be included was 0.08 m $s^{-1}$. The number of valid half-hour measurements averaged is indicated below each box and the boxes are defined as in Figure 3. The average daily (24-hour) NEE for the 34-day period was -0.94 μmol $m^{-2}$ $s^{-1}$ with gaps filled using the mean diurnal variation approach.

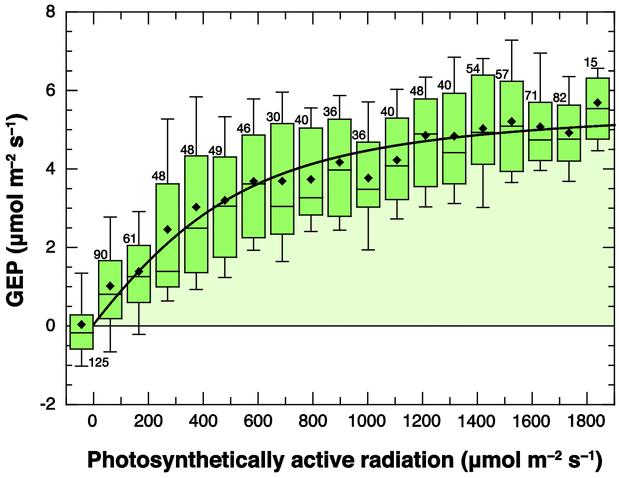


Figure 6. Light response curve determined from all individual 30-minute eddy covariance measurements at the EC flux tower for the period 09 July 2014 to 11 August 2014. The graph shows gross ecosystem photosynthesis (GEP) calculated as the measured average flux at PPFD = 0 (i.e. at night, $R$ = 1.36 µmol m$^{-2}$ s$^{-1}$) minus the measured daytime net ecosystem exchange (NEE). The black curve is a best fit for Equation (7) with parameters $P_m$ = 5.74 µmol m$^{-2}$ s$^{-1}$, $\phi$ = 0.0090 and $C$ = 0.7. The night-time $u_*$ threshold to determine $R$ was 0.08 m s$^{-1}$. The number of valid half-hour measurements averaged is indicated above or below each box and the boxes are defined as in Figure 3.

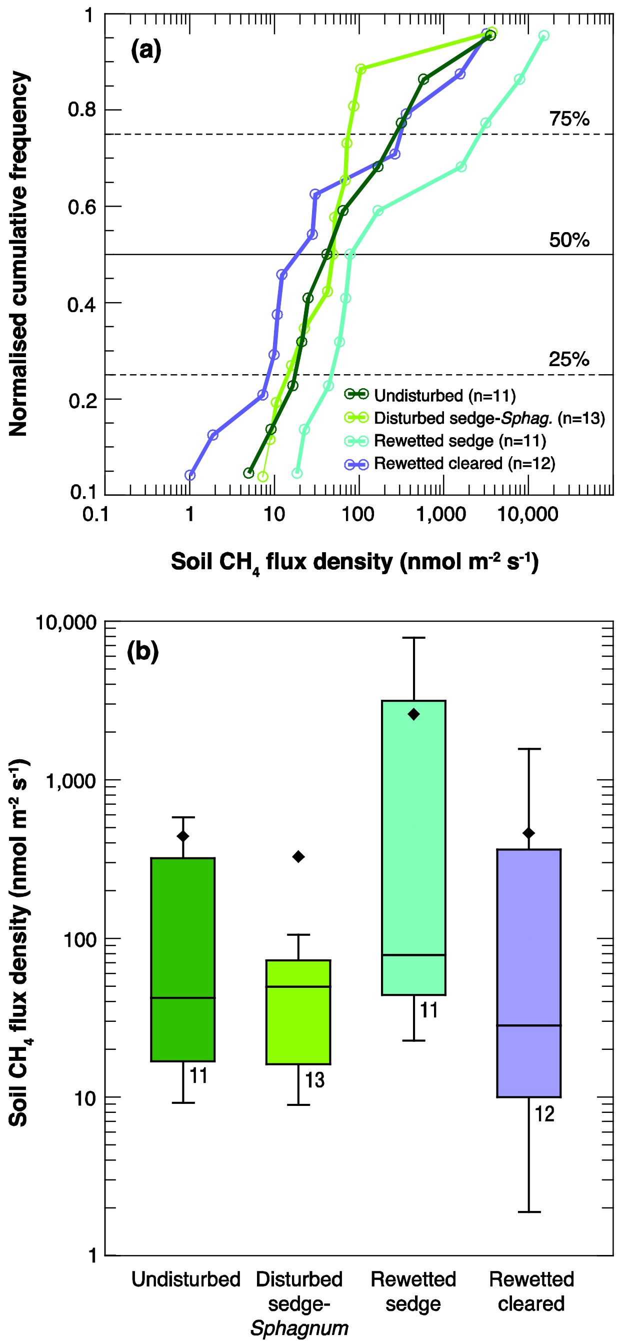


Figure 7. (a) Cumulative frequency distributions of individual soil methane ($CH_4$) flux measurements (all sites and all collars). Data from 17–18 and 24–28 July, and 11 August 2014, are included. In order to visualise the large range of measured efflux values, the $x$-axis is shown on a logarithmic scale. Two points were negative and are not shown. (b) Distribution of soil $CH_4$ flux measurements (all valid runs from all collars, n = 47) for the same time intervals as in (a). In order to visualise the large range of measured efflux values, the $y$-axis is shown on a logarithmic scale.

## Soil methane fluxes

All measured soil $CH_4$ fluxes were positive and ranged over five orders of magnitude, with a highly skewed distribution. To compare sites we used cumulative frequency distributions (Figure 7a) and median values (Figure 7b) in addition to averages. The highest median (50$^{th}$ percentile) lux was measured at the rewetted sedge site at 78 (range: 19–15,000) nmol m$^{-2}$ s$^{-1}$, followed by the disturbed sedge - *Sphagnum* site at 49 (7–3,700) nmol m$^{-2}$ s$^{-1}$, and the undisturbed site at 42 (5–3,500) nmol m$^{-2}$ s$^{-1}$. The lowest median soil $CH_4$ flux was found at the rewetted cleared site at 28 (1–3,200) nmol m$^{-2}$ s$^{-1}$. Over all sites and collars, the median $CH_4$ flux measured was 53 nmol m$^{-2}$ s$^{-1}$ ($n$ = 48).

At all sites, spatial and temporal variability was high. In addition to a site-by-site comparison, we separated individual collars at all sites into four classes based on the dominant vegetation inside the collar (bare / open water, *Sphagnum*, sedges and woody vegetation). We found that mean $CH_4$ fluxes across sites varied substantially among different vegetation types. For collars where vegetation was present, the average (median) emissions for sedges were 1,425 (50) nmol $CH_4$ $m^{-2}$ $s^{-1}$ (n = 23). Collars with *Sphagnum* exhibited 419 nmol (55) $CH_4$ $m^{-2}$ $s^{-1}$ (n = 11). The lowest fluxes were measured from collars containing woody vegetation with 18 (21) nmol $CH_4$ $m^{-2}$ $s^{-1}$ (n = 4). Highest $CH_4$ emissions were found from collars over bare surfaces or open water (ponding) with 3,336 (2,670) nmol $CH_4$ $m^{-2}$ $s^{-1}$ (n = 9) compared to collars containing any of the three types of vegetation with 986 (47) nmol $CH_4$ $m^{-2}$ $s^{-1}$ (n = 38). Over all sites, the lowest fluxes were measured on 24–25 July 2014, immediately after a rain event; and the highest fluxes were measured at the end of a 17-day period with warm summer temperatures and no rain, on 11 August 2014 (see also Figure 2).

## Soil nitrous oxide fluxes

Soil $N_2O$ fluxes at all sites were generally small and ranged between -0.058 nmol $N_2O$ $m^{-2}$ $s^{-1}$ (weak uptake) and 0.052 nmol $N_2O$ $m^{-2}$ $s^{-1}$ (weak emission). Figure 8a shows the cumulative frequency distributions of all soil $N_2O$ flux measurements sorted by site. The highest median (50$^{th}$ percentile) flux was measured at the undisturbed site with a value of 0.014 nmol $N_2O$ $m^{-2}$ $s^{-1}$ (Figure 8b). The disturbed sedge - *Sphagnum* site showed a median flux of -0.013 nmol $N_2O$ $m^{-2}$ $s^{-1}$ (very weak uptake). The other two sites (rewetted sedge, rewetted cleared) showed median values close to zero. Out of the 60 measurements, 24 measurements were negative (uptake) and the overall median was 0.005 nmol $N_2O$ $m^{-2}$ $s^{-1}$ (very weak emission).

## $CO_2$ equivalent fluxes

The combined GHG emissions of all three measured GHGs are shown as $CO_2$ equivalent emissions in Table 3 calculated (following Equation [10]) once as the average from all collars and once using the median values for $CH_4$ and $N_2O$ (to avoid bias towards individual extreme measurements). When average values were considered, the soils at all four sites exhibited strong GHG emissions dominated by $CH_4$. The highest overall $CO_2$e emissions originated from the rewetted sedge site (102.1 g $CO_2$e $m^{-2}$ $day^{-1}$). All other sites exhibited between 15 and 20 % of the rewetted sedge emissions with values of 20.9 (rewetted cleared), 20.9 (undisturbed) and 15.7 (disturbed sedge - *Sphagnum*) g $CO_2$e $m^{-2}$ $day^{-1}$. On average, $CH_4$ was responsible for 98 % (rewetted sedge), 81 % (rewetted cleared), 82 % (undisturbed) and 81 % (disturbed sedge - *Sphagnum*) of all emissions. The remainder was attributable to $CO_2$ emissions. The effect of $N_2O$ on total emissions was negligible and ranged between 0 % (rewetted sedge) and +0.05 % (undisturbed) of the total $CO_2$e emissions. $CO_2$e median fluxes were 5.49

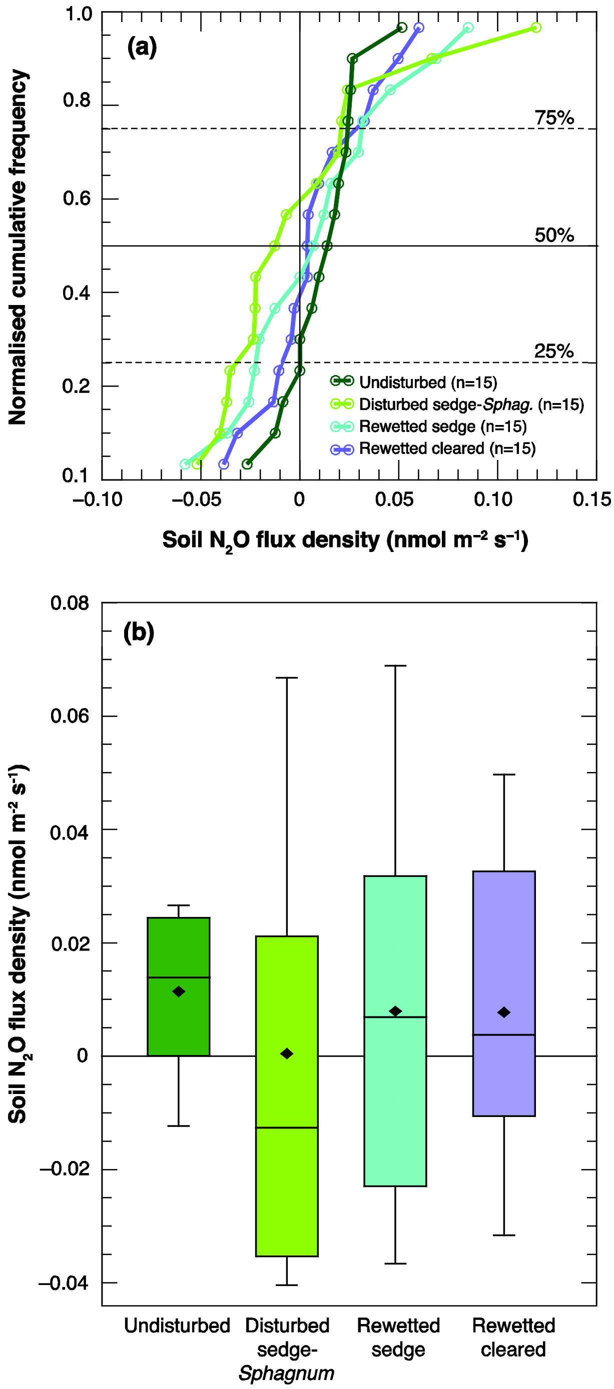


Figure 8. (a) Cumulative frequency distributions of all individual nitrous oxide ($N_2O$) fluxes (all sites and all collars). Data from 17–18 July, 24–28 July and 11 August 2014 are included. (b) Distribution of soil $N_2O$ flux measurements (all sites and all collars). Data from 17–18 July, 24–28 July and 11 August 2014 are included.

Table 3. Calculated total 100-yr global warming potential (GWP; g $CO_2$e $m^{-2}$ $day^{-1}$) by site and greenhouse gases (GHG) based on measured average and median summertime fluxes from all collars at each of the four chamber sites.

| Site | **Average fluxes** (g $CO_2$e $m^{-2}$ $day^{-1}$) | | | | **Median fluxes** (for $CH_4$ and $N_2O$) (g $CO_2$e $m^{-2}$ $day^{-1}$) | | | |
|---|---|---|---|---|---|---|---|---|
| | $CO_2$[(a)] | $CH_4$ | $N_2O$ | Total | $CO_2$[(a)] | $CH_4$ | $N_2O$ | Total |
| Undisturbed | 3.87 (18.5 %) | 17.05 (81.5 %) | 0.01 (0.05 %) | **20.93** (100 %) | 3.87 (70.5 %) | 1.62 (29.5 %) | 0.00 (0.01 %) | **5.49** (100 %) |
| Disturbed sedge - *Sphagnum* | 2.96 (18.9 %) | 12.71 (81.1 %) | 0.00 (0.00 %) | **15.67** (100 %) | 2.96 (60.8 %) | 1.91 (39.2 %) | 0.00 (-0.01 %) | **4.87** (100 %) |
| Rewetted sedge | 2.05 (2.0 %) | 100.02 (98.0 %) | 0.01 (0.01 %) | **102.08** (100 %) | 2.05 (40.3 %) | 3.03 (59.7 %) | 0.00 (0.00 %) | **5.08** (100 %) |
| Rewetted cleared | 3.12 (14.9 %) | 17.77 (85.0 %) | 0.01 (0.04 %) | **20.90** (100 %) | 3.12 (74.1 %) | 1.09 (25.9 %) | 0.00 (0.00 %) | **4.21** (100 %) |

[(a)] Soils and ground vegetation only. Modelled values over the period based on empirical relations (see text).

(undisturbed), 5.08 (rewetted sedge), 4.87 (disturbed sedge - *Sphagnum*), and 4.21 (rewetted cleared) g $CO_2$e $m^{-2}$ $day^{-1}$. As median values, $CH_4$ was responsible for 60 % (rewetted sedge), 39 % (disturbed sedge - *Sphagnum*), 30 % (undisturbed) and 26 % (rewetted cleared) of all emissions.

## DISCUSSION

During the period of the study, $CH_4$ was the dominant GHG emitted at all study sites within the BBECA and our measurements showed that all these sites are a significant source of $CH_4$. Fluxes in the rewetted (water-saturated) sedge ecosystem were highest, with a quarter of the values higher than 3,000 mg $CH_4$ $m^{-2}$ $day^{-1}$ (median 78 mg $CH_4$ $m^{-2}$ $day^{-1}$). Median $CH_4$ fluxes at the rewetted sedge site were 1.6 to 2.7 times higher than at the other three sites. The rewetted sedge site experienced a high water table (mostly at the surface) with an average water table depth of only 0.03 m throughout the summer. While most measurements represent diffusive fluxes, ebullition can be an important mechanism under conditions of changing pressure and temperature (Fechner-Levy & Hemond 1996), and due to changes in water table depth (Baird *et al*. 2004, Meng *et al*. 2012). Visible ebullition was observed at our rewetted sedge site. In soil columns taken from a raised bog, Baird *et al*. (2004) found that $CH_4$ emissions from diffusive efflux were similar to those from ebullition, and van der Nat & Middelburg (1998) showed that $CH_4$ was emitted almost exclusively by ebullition in non-vegetated wetlands with otherwise identical sediment. While we attempted to measure true diffusion and ebullition by installing boardwalks in selected areas with wet soils, disturbance due to traffic during sampling in other areas might have caused increased ebullition, thereby affecting selected measurements (of which 13 were removed).

The large variability of the remaining $CH_4$ fluxes, which range over several orders of magnitude between the five collars at each site and between measurement dates, is a challenge for proper quantification of fluxes with limited manual measurements. The values presented in this study are associated with large spatial and temporal variability. For example, the rewetted sedge, disturbed sedge - *Sphagnum* and undisturbed sites exhibited simultaneous drying over the summer and showed a variable microtopography where aerobic (e.g. hummocks) and anaerobic (e.g. hollows) conditions existed at the same site. We argue that cumulative frequency distributions (Figure 7a) are better suited to characterising differences between sites than reporting averages. Based on this approach, $CH_4$ fluxes were found to decrease in the order of rewetted sedge > undisturbed ≈ disturbed sedge - *Sphagnum* > rewetted cleared.

When anaerobic conditions are present,

vegetation type controls the rate of $CH_4$ emissions. $CH_4$ fluxes are highest in micro-environments where the water table is at the surface and a ready supply of fresh biomass is available (e.g. Bellisario *et al.* 1999, McEwing *et al.* 2015). Firstly, the availability of new living plant material in the micro-environment is important (Couwenberg 2009). Secondly, $CH_4$ emissions vary greatly due to differences in the effectiveness of vascular plants (primarily sedges) in transporting $CH_4$ from the water-saturated zone through their aerenchyma (gas conductive plant tissues) to the atmosphere (Smith *et al*. 2003, Laanbroek 2010). Our finding that the highest $CH_4$ emissions were from collars over bare surfaces or open water (ponding) as opposed to any type of vegetation is in contrast to the results of Mahmood & Strack (2011), who measured $CH_4$ fluxes from a peatland under restoration in eastern Canada and found a significant positive correlation between vegetation volume and $CH_4$ fluxes.

The spatial variability in $CH_4$ emissions can be further explained by the variability in water table depth (e.g. Moore & Roulet 1993) and microbial communities (e.g. Hendriks *et al.* 2010, Schrier-Uijl *et al.* 2010, Teh *et al.* 2011, Baldocchi *et al.* 2012) across the sites. For a given vegetation class (bare soil or standing water, *Sphagnum*, sedges, woody vegetation), there was a weak indication of an increase in $CH_4$ emissions with an increase in soil water content (except for the woody vegetation class due to low sample size). Slightly tighter relationships between water table depth and $CH_4$ emissions were observed, with emissions decreasing for *Sphagnum*, sedges and bare soil (but increasing for woody vegetation) in response to deeper water tables. Previous studies have concluded that when the water table is more than 0.25 m below the surface, $CH_4$ emissions can usually be considered to be negligible (Strack & Waddington 2012). In the current study, a water table closer than 0.20 m to the surface produced average emissions of 2,518 nmol $CH_4$ $m^{-2}$ $s^{-1}$. For water table depth > 0.20 m, average emissions were 890 nmol $CH_4$ $m^{-2}$ $s^{-1}$ when all sites and vegetation types were considered.

Table 4 compares $CH_4$ fluxes recorded in various peatlands in temperate/boreal North America to the four chamber sites in the current study. The average $CH_4$ fluxes reported in this study are substantially higher than for all pristine North American peatlands. There are several possible explanations for the high $CH_4$ fluxes in the BBECA. Firstly, the two rewetted study sites in the BBECA were rewetted only recently (2–6 years ago) (Table 1) and are thus similar to the more recently restored wetland in the San Joaquin delta (Knox *et al.* 2015). In the first phase after rewetting (~5–20 years), $CH_4$ emissions are known to be high, with rewetted bogs becoming major GHG sources (Strack & Waddington 2012). Secondly, $CH_4$ measurements were made during the warmest time of the year (and only in the daytime), when microbial activity was optimal, while the selected studies in Table 4 represent either seasonal or annual averaged fluxes. Median values of the $CH_4$ fluxes are comparable to the results of other studies that investigated restored wetlands outside North America (e.g. Hendriks *et al.* 2007, Schrier-Uijl *et al.* 2014).

The GHG exchange of $CO_2$ due to photosynthesis and respiration was of secondary importance compared to $CH_4$. Overall, soil and low-growing vegetation were a small net source of $CO_2$ at all chamber sites, where respiration dominated over photosynthesis. The rewetted sedge site with its water-saturated soil and water level above the surface for many collars consistently displayed the lowest respiration rates compared to the other three sites, probably due to limited oxygen availability. However, the ecosystem-wide fluxes determined at the EC flux tower showed that the ecosystem overall, including the tall-stature vegetation (shrubs, tall sedges), was a moderate $CO_2$ sink (NEE = -3.59 g $CO_2$ $m^{-2}$ $day^{-1}$) during the summer months. The EC flux measurements determine the net fluxes of the entire ecosystem (including tall vegetation). For the complete ecosystem, measured by EC, $CO_2$ uptake *via* photosynthesis of grasses and shrubs exceeded soil respiration.

Table 5 compares the NEE measured at the flux tower between 09 July and 11 August to summertime NEE measurements over several other wetlands in temperate and boreal North America. Note that most studies report NEE from undisturbed wetlands, all of which are $CO_2$ sinks (negative NEE). The values in our study compare well with the range of values reported for similar ecosystems under comparable climatic conditions. Compared to other previously disturbed and restored wetlands, the summertime $CO_2$ sink in this study (six years after rewetting) is only one third that of a recently rewetted/restored wetland in the San Joaquin delta (Knox *et al.* 2015, ~11 g $CO_2$ $m^{-2}$ $day^{-1}$) but is stronger than a recently restored peatland in the continental climate of Alberta, Canada (Strack *et al.* 2014, ~ -0.8 g $CO_2$ $m^{-2}$ $day^{-1}$). A long-term restored wetland in the San Joaquin delta (15 years after restoration was initiated, Knox *et al.* (2015) shows a summertime carbon sink that is about five times stronger than in our study.

Table 6 compares NEE, $R_e$ and GEP at the EC flux tower to values measured over other land cover in the same region at the same time of year (hence

Table 4. Comparison of average methane ($CH_4$) fluxes (and median values in square brackets) measured in this study with averages reported in the literature on fluxes from wetlands in temperate / boreal North America. Studies are sorted from high to low $CH_4$ emissions. The fourth column refers to the measurement method, where "CH" means chamber technique, "EC" means eddy covariance technique; the fifth column refers to the period of measurements, where "YR" are year-round, "SA" are seasonal (summer season or growing season) averages, and "SP" are sporadic measurements limited in time.

| **Study** | **Location** | **Ecosystem** | **Method** | **Period** | **Reported $CH_4$ emissions** (nmol $m^{-2}$ $s^{-1}$) |
|---|---|---|---|---|---|
| Waddington & Day (2007) | QC, Canada | Restored peatland | CH | SP | **341** |
| Treat *et al.* (2007) | NH, USA | Poor fen | CH | SA | **147 – 305** |
| Chasar *et al.* (2000) | MN, USA | Rich fen | CH | SP | **120 – 206** |
| Mahmood &Strack (2011) | QC, Canada | Restored rich fen | CH | SA | **7.2 – 174** |
| Chasar *et al.* (2000) | MN, USA | Ombrotrophic bog | CH | SP | **20 – 174** |
| Shannon & White (1994) | MI, USA | Ombrotrophic bog | CH | YR | **0.4 – 151** |
| Knox *et al.* (2015) | CA, USA | Rewetted wetland (for 2 years) | EC | YR | **140** |
| Dise (1993) | MN, USA | Poor fen | CH | YR | **130** |
| Knox *et al.* (2015) | CA, USA | Restored wetland (for 15 years) | EC | YR | **102** |
| Dise (1993) | MN, USA | Ombrotrophic bog | CH | YR | **85** |
| This study (rewetted sedge) | BC, Canada | Disturbed and rewetted (for 6 years) bog | CH | SP | **78**[(a)] [2577] [(b)] |
| This study (disturbed sedge - *Sphagnum*) | BC, Canada | Disturbed ombrotrophic bog | CH | SP | **49**[(a)] [328][(b)] |
| This study (undisturbed) | BC, Canada | Undisturbed ombrotrophic bog | CH | SP | **42**[(a)] [439][(b)] |
| Nadeau *et al.* (2013) | QC, Canada | Ombrotrophic bog | EC | SN | **42** |
| Strack *et al.* (2014) | AB, Canada | Restored peatland | CH | SA | **37.9** |
| Hanis *et al.* (2015) | MB, Canada | Subarctic fen | EC | SP | **37** |
| This study (rewetted cleared) | BC, Canada | Disturbed and rewetted (for 2 years) bog | CH | SP | **28**[(a)] [458][(b)] |
| Moore *et al.* (1994) | ON, Canada | Poor fen | CH | SP | **9.4 – 24** |
| Moore & Knowles (1990) | QC, Canada | Poor fen | CH | YR | **19** |
| Moore *et al.* (1994) | ON, Canada | Ombrotrophic bog | CH | SP | **0.1 – 9.4** |
| Strack & Zuback (2013) | QC, Canada | Restored peatland (for 10 years) | CH | SA | **6.3** |
| Moore & Knowles (1990) | ON, Canada | Rich fen | CH | YR | **5.9** |
| Roulet *et al.* (1992) | QC, Canada | Ombrotrophic bog | CH | SN | **4.2** |
| Strack & Zuback (2013) | QC, Canada | Disturbed, unrestored peatland | CH | SA | **3.7** |
| Roulet *et al.* (1992) | ON, Canada | Poor fen | CH | SN | **2.2** |
| Moore & Knowles (1990) | QC, Canada | Ombrotrophic bog | CH | YR | **0.2** |

[(a)] Median, [(b)] Average.

Table 5. Comparison of summertime net ecosystem exchange (NEE) measured in various undisturbed and restored temperate and boreal wetlands in North America using eddy covariance (EC) with the EC-measured values in this study. For comparison, the results of selected chamber studies from rewetted peatlands are also shown. Entries are sorted by increasing NEE (strongest $CO_2$ sink at top, weakest sink at bottom).

| **Study** | **Location** | **Ecosystem** | **Method** | **Study period** | **NEE** ($g\ CO_2\ m^{-2}\ day^{-1}$) | $T_a$ (ºC) |
|---|---|---|---|---|---|---|
| Knox *et al.* (2015) | CA, USA | Long-term restored wetland (rewetted for 15 years) | EC | Jun – Aug | **~ -18** | 16.6[c] |
| Knox *et al.* (2015) | CA, USA | Recently restored wetland (rewetted for 2 years) | EC | Jun– Aug | **~ -11** | 19.6[c] |
| Sulman *et al.* (2009) | WI, USA | Fen | EC | Jun – Aug | **-8.1** | 15.7 |
| Neumann *et al.* (1994) | ON, Canada | Water-stressed bog | EC | 01 Jul – 29 Jul | **-5.9** | - |
| Roulet *et al.* (2007) | ON, Canada | Ombrotrophic bog | EC | Jun – Aug | **-5.7** | 20.9 |
| Sulman *et al.* (2010) | WI, USA | Wet meadow / marsh fen | EC | Jun – Aug | **-3.7** | 15.2 |
| **This study** (flux tower) | BC, Canada | Restored ombrotrophic bog (rewetted for 6 years) | EC | 09 Jul – 11 Aug | **-3.6** | 18.6 |
| Syed *et al.* (2006) | AB, Canada | Peatland | EC | May – Oct | **-3.5** | 16.5 [b] |
| Sonnentag *et al.* (2010) | SK, Canada | Minerotrophic fen | EC | May – Oct | **-3.5** | 16.2 |
| Lafleur *et al.* (2003) | ON, Canada | Ombrotrophic bog | EC | Jun – Sep | **-2.3** | 22.3 |
| Adkinson *et al.* (2011) | AB, Canada | Poor fen | EC | May – Oct | **-2.2** | 9.0 |
| Shurpali *et al.* (1995) | MN, USA | Peatland | EC | May – Oct | **-1.8** | 14.9 |
| Pelletier *et al*. (2015) | QC, Canada | Peatland | EC | May – Oct | **-1.8** | 15.6 |
| Adkinson *et al.* (2011) | AB, Canada | Rich fen | EC | May – Oct | **-1.5** | 10.6 |
| Strack *et al.* (2014) | AB, Canada | Restored peatland (restored for 3 years) | CH | May – Oct | **-0.8** | - |
| Sulman *et al.* (2010) | WI, USA | Ombrotrophic bog | EC | Jun – Aug | **-0.7** | - |
| Waddington *et al*. (2010) | QC, Canada | Restored peatland | CH | May – Oct | **-0.5** | 18.0 |
| Hanis *et al*. (2015) | MB, Canada | Subarctic fen | EC | Jun – Oct | **-0.2** | 7.4 |

[a] eddy covariance (EC) or chamber measurements (CH, only for restored surfaces) [b] July temperature only. [b] Aug–Sep temperature.

Table 6. Comparison of summertime net ecosystem exchange (NEE), ecosystem respiration ($R_e$) and ecosystem photosynthesis (GEP), over different vegetated land covers in the Vancouver region where EC measurements of $CO_2$ fluxes have been carried out. Entries are sorted by decreasing -NEE/GEP ratio.

| EC-Site | Land use / cover | Period | Summertime daily $CO_2$ fluxes ($g\ CO_2\ m^{-2}\ day^{-1}$) | | | -NEE/GEP (%) |
|---|---|---|---|---|---|---|
| | | | NEE | $R_e$ | GEP (GEP/NEE) | |
| **Burns Bog (this study)** Delta, BC | Raised bog | 09 Jul – 11 Aug, 2014 | **-3.59** | **5.17** | **8.76** | **41 %** |
| **Westham Island** (CA-Wes)[a] Delta, BC | Unmanaged grassland | 01 Jul – 31 Jul, 2009 | -4.77 | 17.21 | 21.98 | 22 % |
| **Campbell River** (CA-Ca1)[a], Vancouver Island | Douglas-fir forest (~55 yrs) | July average 2002 – 2006 | -3.54 | 38.94 | 42.48 | 8 % |
| **Buckley Bay** (CA-Ca3)[a], Vancouver Island | Douglas-fir forest (~15 yrs) | July average 2002 – 2006 | -1.77 | 24.19 | 25.96 | 7 % |

[a] Site identifier in global Fluxnet database (http://fluxnet.ornl.gov).
[b] Data from Krishnan *et al.* (2009) before fertilisation.

experiencing the same climate). NEE at an unmanaged grassland site 15 km to the west of Burns Bog in the Fraser River Delta (Westham Island, Delta, BC) was 1.3 times that in Burns Bog. At that site, $R_e$ and GEP values were higher by a factor of 3.3 and 2.5, respectively, compared to our study site in the BBECA. A mature 55-year-old forest on Vancouver Island (200 km NW; Krishnan *et al.* 2009) showed a typical NEE value in July that is close to NEE at our study site, but actual rates of $R_e$ and GEP were higher by factors of eight and five, respectively. Finally, in comparison to a young forest plantation (Buckley Bay, 150 km W; Krishnan *et al.* 2009), our site sequesters almost twice the amount of $CO_2$, even though $R_e$ is five and GEP is three times larger in the young and growing forest. Compared to other ecosystems in the same region, the disturbed and rewetted bog is not an ecosystem of high productivity but one with considerably limited respiration that makes the sequestration of assimilated $CO_2$ more efficient (-NEE is 41 % of GPP, as opposed to 22 % for the unmanaged grassland site 15 km to the west). The limited respiration is attributed to the shallow water table resulting from the ditch blocking that causes anaerobic conditions. A similar effect has been reported for a restored vacuum-harvested peatland in eastern Canada (Waddington *et al.* 2010).

No significant emission or uptake of $N_2O$ was found, indicating that $N_2O$ is probably not significant in comparison to $CH_4$ and $CO_2$, in part because the nutrient-poor bog has no substantial sources of nitrogen. This is consistent with the findings of Hendriks *et al.* (2007) and the compilation by Wilson *et al.* (2016), who show negligible $N_2O$ fluxes over rewetted organic soils.

The summertime chamber measurements provided information on GHG fluxes for the latter part of the growing season when the water table was lowest and air temperatures highest. However, it is not possible to derive annual averages with the temporally limited data available for this study period, and further measurements using EC measurements are currently ongoing. Overall, the results showed that $CH_4$ emissions dominated over net GHG emissions. Managing the water table could be a strategy for mitigating $CH_4$ emissions during the initial rewetting period, but such a strategy would require more detailed monitoring of GHG emissions to obtain annual estimates and isolate more carefully the major controls on emissions.

## ACKNOWLEDGEMENTS

This study was funded by Metro Vancouver through a research agreement with the University of British Columbia (PI: A. Christen / A. Black) and supported by CFI (Canada Foundation for Innovation) and British Columbia Knowledge Development Fund (BCKDF) grants (Christen / Johnson). We thank Dr Conor Reynolds and his team at Metro Vancouver and the BBECA for providing the opportunity to pursue this research. Sarah Howie (municipality of Delta, BC) provided dipwell data on the water table. We thank Johannes Exler, Rick Ketler, Eric Leinberger, Dan Moore, Zoran Nesic, Katrin Schmid, Joe Soluri, Alice Stevenson and Yuexian Wang (all UBC) for their contributions to project, data, laboratory and field work. We thank the two reviewers and the editor for their valuable input to discussions.

## REFERENCES

Adkinson, A.C., Syed, K.H. & Flanagan, L.B. (2011) Contrasting responses of growing season ecosystem $CO_2$ exchange to variation in temperature and water table depth in two peatlands in northern Alberta, Canada. *Journal of Geophysical Research Biogeosciences*, 116, G01004.

Baird, A.J., Beckwith, C.W., Waldron, S. & Waddington, J.M. (2004) Ebullition of methane-containing gas bubbles from near-surface *Sphagnum* peat. *Geophysical Research Letters*, 31, L21505, doi:10.1029/2004GL021157.

Baldocchi, D., Detto, M., Sonnentag, O., Verfaillie, J., Teh, Y., Silver, W. & Kelly, M. (2012) The challenges of measuring methane fluxes and concentrations over a peatland pasture. *Agricultural and Forest Meteorology*, 153, 177–187.

Bellisario, L.M., Bubier, J.L., Moore, T.R. & Chanton, J.P. (1999) Controls on $CH_4$ emissions from a northern peatland. *Global Biogeochemical Cycles*, 13(1), 81–91.

Biggs, W.G. (1976) *An Ecological and Land Use Study of Burns Bog, Delta, British Colombia*. MSc dissertation, Department of Plant Science, The University of British Columbia, Vancouver, 171 pp.

Bleuten, W., Borren, W., Glaser, P.H., Tsuchihara, T., Lapshina, E.D, Mäkilä, M., Siegel, D., Joosten, H. & Wassen, M.J. (2006) Hydrological processes, nutrient flows and patterns of fens and bogs. In: Verhoeven, J.T.A., Beltman, B., Bobbink, R. & Whigham, D.F. (eds.) *Wetlands and Natural Resource Management*, Ecological Studies 190, Springer-Verlag, Berlin Heidelberg, 183–204.

Chasar, L.S., Chanton, J.P., Glaser, P.H. & Siegel, D.I. (2000) Methane concentration and stable isotope distribution as evidence of rhizospheric processes: comparison of a fen and bog in the Glacial Lake Agassiz peatland complex. *Annals of Botany*, 86(3), 655–663.

Ciais, P., Sabine, C., Bala, G., Bopp, L., Brovkin, V., Canadell, J., Chhabra, A., DeFries, R., Galloway, J., Heimann, M., Jones, C., Le Quéré, C., Myneni, R.B., Piao, S. & Thornton, P. (2013) Carbon and other biogeochemical cycles. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V. & Midgley, P.M. (eds.) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 465–570.

Couwenberg, J. (2009) Methane emissions from peat soils (organic soils, histosols): facts, MRV-ability, emission factors. Wetlands International, Ede, The Netherlands, 14 pp. Online at: http://www.imcg.net/media/download_gallery/climate/couwenberg_2009b.pdf

Crawford, B. & Christen, A. (2015) Spatial source attribution of measured urban eddy covariance $CO_2$ fluxes. *Theoretical and Applied Climatology*, 119(3–4), 733–755.

Crawford, B., Christen, A. & Ketler, R. (2009) *Processing and Quality Control Procedures of Turbulent Flux Measurements During the Vancouver EPiCC Experiment*. EPiCC Technical Report, Vol. 1, 11 pp. Online at: http://hdl.handle.net/ 2429/45079

Dinsmore, K.J., Skiba, U.M., Billett, M.F., Rees, R.M. & Drewer, J. (2009) Spatial and temporal variability in $CH_4$ and $N_2O$ fluxes from a Scottish ombrotrophic peatland: Implications for modelling and up-scaling. *Soil Biology and Biochemistry*, 41(6), 1315–1323.

Dise, N.B. (1993) Methane emission from Minnesota peatlands: Spatial and seasonal variability. *Global Biogeochemical Cycles*, 7(1), 123–142.

Drewitt, G.B., Black, T.A., Nesic, Z., Humphreys, E.R., Jork, E.M., Swanson, R., Ethier, G.J., Griffis, T. & Morgenstern, K. (2002) Measuring forest floor $CO_2$ fluxes in a Douglas-fir forest. *Agricultural and Forest Meteorology*, 110(4), 299–317.

Falge, E., Baldocchi, D., Olson, R., Anthoni, P., Aubinet, M., Bernhofer, C., Burba, G., Ceulemans, R., Clement, R., Dolman, H., Granier, A., Gross, P., Grünwald, T., Hollinger, D., Jensen, N.-O., Katul, G., Keronen, P., Kowalski, A., Lai, C.T., Law, B.E., Meyers, T., Moncrieff, J., Moors, E., Munger, J.W., Pilegaard, K., Rannik, U., Rebmann, C., Suyker, A., Tenhunen, J., Tu, K., Verma, S., Vesala, T, Wilson, K. & Wofsy, S. (2001) Gap filling strategies for defensible annual sums of net ecosystem exchange. *Agricultural and Forest Meteorology*, 107(1), 43–69.

Fechner-Levy, E.J., & Hemond, H.F. (1996) Trapped methane volume and potential effects on methane ebullition in a northern peatland. *Limnology and Oceanography*, 41, 1375–1383.

Göttlich, K.H., Richard, K.-H., Kuntze, H., Egglesmann, R., Günther, J., Eichelsdörfer, D. & Briemle, G. (1993) Mire utilization. In: Heathwaite, A.L. & Göttlich, K.H. (eds.) *Mires: Process, Exploitation and Conservation*. John Wiley & Sons Ltd., Chichester, 516 pp.

Hanis, K.L., Amiro, B.D., Tenuta, M., Papakyriakou, T. & Swystun, K.A. (2015) Carbon exchange over four growing seasons for a subarctic sedge fen in northern Manitoba, Canada. *Arctic Science*, 27–44.

Hebda, R.J., Gustavson, K., Golinski, K. & Calder, A.M. (2000) *Burns Bog Ecosystem Review Synthesis Report for Burns Bog, Fraser River Delta, South-western British Columbia, Canada*. Environmental Assessment Office, Victoria, BC, 270 pp. plus Appendices A–I.

Hendriks, D.M.D., van Huissteden, J. & Dolman, A.J. (2010) Multi-technique assessment of spatial and temporal variability of methane fluxes in a peat meadow. *Agricultural and Forest Meteorology*, 150(6), 757–774.

Hendriks, D.M.D., van Huissteden, J., Dolman, A.J. & van der Molen, M.K. (2007) The full greenhouse gas balance of an abandoned peat meadow. *Biogeosciences*, 4(3), 411–424.

Howie, S.A., Whitfield, P.H., Hebda, R.J., Munson, T.G., Dakin, R.A. & Jeglum, J.K. (2009) Water table and vegetation response to ditch blocking: restoration of a raised bog in southwestern British Columbia. *Canadian Water Resources Journal / Revue canadienne des ressources hydriques*, 34(4), 381–392.

IPCC (2014) 2013 *Supplement to the 2006 IPCC Guidelines for National Greenhouse Gas Inventories: Wetlands*. Hiraishi, T., Krug, T., Tanabe, K., Srivastava, N., Baasansuren, J., Fukuda, M. & Troxler, T.G. (eds.), IPCC, Switzerland. Online at: http://www.ipcc-nggip.iges.or.jp/public/wetlands/

Jassal, R.S., Black, T.A., Cai, T., Morgenstern, K., Li, Z., Gaumont-Guay, D. & Nesic, Z. (2007) Components of ecosystem respiration and an estimate of net primary productivity of an intermediate-aged Douglas-fir stand. *Agricultural and Forest Meteorology*, 144(1–2), 44–57.

Jassal, R.S., Black, T.A., Chen, B., Roy, R., Nesic, Z., Spittlehouse, D.L. & Trofymow, J.A. (2008) $N_2O$ emissions and carbon sequestration in a nitrogen-fertilized Douglas fir stand. *Journal of Geophysical Research: Biogeosciences*, 113(G4), G04013.

Jassal, R.S., Black, T.A., Nesic, Z. & Gaumont-Guay, D. (2012) Using automated non-steady-state chamber systems for making continuous long-term measurements of soil $CO_2$ efflux in forest ecosystems. *Agricultural and Forest Meteorology*, 161, 57–65.

Jassal, R., Black, A., Novak, M., Morgenstern, K., Nesic, Z. & Gaumont-Guay, D. (2005) Relationship between soil $CO_2$ concentrations and forest-floor $CO_2$ effluxes. *Agricultural and Forest Meteorology*, 130(3–4), 176–192.

Jassal, R.S., Black, T.A., Roy, R. & Ethier, G. (2011) Effect of nitrogen fertilization on soil $CH_4$ and $N_2O$ fluxes, and soil and bole respiration. *Geoderma*, 162(1–2), 182–186.

Joosten, H. (2013) For peat's sake - bogs and climate change. Recorded presentation at the Environmental Protection Agency of Ireland. Online at: http://www.epa-pictaural.com/s/climateChange/Joosten1.php?playVideo=true

Kivimäki, S.K., Yli-Petäys, M. & Tuittila, E.-S. (2008) Carbon sink function of sedge and *Sphagnum* patches in a restored cut-away peatland: increased functional diversity leads to higher production. *Journal of Applied Ecology*, 45, 921–929.

Knox, S.H., Sturtevant, C., Matthes, J.H., Koteen, L., Verfaillie, J. & Baldocchi, D. (2015) Agricultural peatland restoration: effects of land-use change on greenhouse gas ($CO_2$ and $CH_4$) fluxes in the Sacramento-San Joaquin Delta. *Global Change Biology*, 21(2), 750–765.

Krishnan, P., Black, T.A., Jassal, R.S., Chen, B. & Nesic, Z. (2009) Interannual variability of the carbon balance of three different-aged Douglas-fir stands in the Pacific Northwest. *Journal of Geophysical Research*, 114, G04011.

Kroon, P.S., Schrier-Uijl, A.P., Hensen, A., Veenendaal, E.M. & Jonker, H.J.J. (2010) Annual balances of $CH_4$ and $N_2O$ from a managed fen meadow using eddy covariance flux measurements. *European Journal of Soil Science*, 61(5), 773–784.

Laanbroek, H.J. (2010) Methane emission from natural wetlands: interplay between emergent macrophytes and soil microbial processes. A mini-review. *Annals of Botany*, 105(1), 141–153.

Lafleur, P.M., Roulet, N.T., Bubier, J.L., Frolking, S. & Moore, T.R. (2003) Interannual variability in the peatland-atmosphere carbon dioxide exchange at an ombrotrophic bog. *Global Biogeochemical Cycles*, 17(2), 1036.


 DOI: 10.19189/MaP.2015.OMB.207

Lloyd, J. & Taylor, J. (1994) On the temperature dependence of soil respiration. *Functional Ecology*, 315–323.

Luo, Y. & Zhou, X. (2006) *Soil Respiration and the Environment*. Academic Press, Burlington, 319 pp.

Madrone Consultants Ltd. (1999) *Burns Bog Ecosystem Review. Plants and Plant Communities*. Report prepared for Delta Fraser Properties Partnership and the Environmental Assessment Office in support of the Burns Bog Ecosystem Review, with additional work on publicly owned lands conducted for the Environmental Assessment Office in association with the Corporation of Delta, Madrone Consultants Ltd., Duncan, BC, 156 pp.

Mahmood, S. & Strack, M. (2011) Methane dynamics of recolonized cutover minerotrophic peatland: Implications for restoration. *Ecological Engineering*, 37, 1859–1868.

Marini, R.P. & Sowers, D.L. (1990) Net photosynthesis, specific leaf weight, and flowering of peach as influenced by shade. *HortScience*, 25(3), 331–334.

McDade, G.J. (2000) *Burns Bog Ecosystem Review*. Report of the special advisor to the Minister of the Environment, British Columbia, 37 pp.

McEwing, K.R., Fisher, J.P. & Zona, D. (2015) Erratum to: Environmental and vegetation controls on the spatial variability of $CH_4$ emission from wet-sedge and tussock tundra ecosystems in the Arctic. *Plant and Soil*, 388(1), 37–52.

Meng, L., Hess, P.G.M., Mahowald, M.N., Yavitt, J.B., Riley, W.J., Subin, Z.M., Lawrence, D.M., Swenson, S.C., Jauhiainen, J. & Fuka, D.R. (2012) Sensitivity of wetland methane emissions to model assumptions: application and model testing against site observations. *Biogeosciences*, 9, 2793–2819, doi:10.5194/bg-9-2793-2012.

Mentzer, J.L., Goodman, R.M. & Balser, T.C. (2006) Microbial response over time to hydrologic and fertilization treatments in a simulated wet prairie. *Plant and Soil*, 284, 85–100.

Metro Vancouver (2007) *Burns Bog Ecological Conservancy Area Management Plan*. Metro Vancouver, Burnaby, BC, Canada, 46pp. Online at: http://www.metrovancouver.org/services/parks/ParksPublications/BurnsBogManagementPlan.pdf

Moore, C.J. (1986) Frequency response corrections for eddy correlation systems. *Boundary-Layer Meteorology*, 37(1–2), 17–35.

Moore, T.R., Heyes, A. & Roulet, N.T. (1994) Methane emissions from wetlands, southern Hudson Bay lowland. *Journal of Geophysical Research: Atmospheres*, 99(D1), 1455–1467.

Moore, T.R. & Knowles, R. (1990) Methane emissions from fen, bog and swamp peatlands in Quebec. *Biogeochemistry*, 11(1), 45–61.

Moore, T.R. & Roulet, N.T. (1993) Methane flux: water table relations in northern wetlands. *Geophysical Research Letters*, 20(7), 587–590.

Myhre, G., Shindell, D., Bréon, F.M., Collins, W., Fuglestvedt, J., Huang, J., Koch, D., Lamarque, J.F., Lee, D., Mendoza, B., Nakajima, T., Robock, A., Stephens, G., Takemura, T. & Zhang, H. (2013) Anthropogenic and natural radiative forcing. In: Stocker, T.F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S.K., Boschung, J., Nauels, A., Xia, Y., Bex, V. & Midgley, P.M. (eds.) *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 659–740.

Nadeau, D.F., Rousseau, A.N., Coursolle, C., Margolis, H.A. & Parlange, M.B. (2013) Summer methane fluxes from a boreal bog in northern Quebec, Canada, using eddy covariance measurements. *Atmospheric Environment*, 81, 464–474.

Neumann, H.H., den Hartog, G., King, K.M. & Chipanshi, A.C. (1994) Carbon dioxide fluxes over a raised open bog at the Kinosheo Lake tower site during the Northern Wetlands Study (NOWES). *Journal of Geophysical Research: Atmospheres*, 99(D1), 1529–1538.

OECD (1996) *Guidelines for Aid Agencies for Improved Conservation and Sustainable Use of Tropical and Sub-tropical Wetlands*. Organization of Economic Co-operation and Development (OECD), Paris, 69 pp. Online at: http://www.oecd.org/dac/environment-development/1887748.pdf

Ögren, E. & Evans, J.R. (1993) Photosynthetic light-response curves. *Planta*, 189(2), 182–190.

Peichl, M., Öquist, M., Löfvenius, M.O., Ilstedt, U., Sagerfors, J., Grelle, A., Lindroth, A. & Nilsson, M. (2014) A 12-year record reveals pre-growing season temperature and water table level threshold effects on the net carbon dioxide exchange in a boreal fen. *Environmental Research Letters*, 9(5), doi:10.1088/1748-9326/9/5/055006.

Pelletier, L., Strachan, I.B., Roulet, N.T. & Garneau, M. (2015) Can boreal peatlands with pools be net sinks for $CO_2$? *Environmental Research Letters*, 10(3), 035002.

Rebmann, C., Kolle, O., Heinesch, B., Queck, R., Ibrom, A. & Aubinet, M. (2012) Data acquisition and flux calculations. In: Aubinet, M., Vesala, T.

& Papale, D. (eds.) *Eddy Covariance*, Springer, The Netherlands, 59–83.

Resources Inventory Committee (1998) *Standard for Terrestrial Ecosystem Mapping in British Columbia*. Ecosystems Working Group, Terrestrial Ecosystems Task Force, Resources Inventory Committee, Victoria, BC, 100 pp. Online at: https://www.for.gov.bc.ca/hts/risc/pubs/ teecolo/tem/tem_man.pdf

Riutta, T., Laine, J. & Tuittila, E.-S. (2007) Sensitivity of $CO_2$ exchange of fen ecosystem components to water level variation. *Ecosystems*, 10, 718–733.

Rochefort, L. & Lode, E. (2006) Restoration of degraded boreal peatlands. In: Wieder, R.K. & Vitt, D.H. (eds.) *Boreal Peatland Ecosystems*, Ecological Studies, Volume 188, Springer-Verlag, Berlin Heidelberg, 382–423.

Roulet, N.T., Ash, R. & Moore, T.R. (1992) Low boreal wetlands as a source of atmospheric methane. *Journal of Geophysical Research: Atmospheres*, 97(D4), 3739–3749.

Roulet, N.T., Lafleur, P.M., Richard, P.J.H., Moore, T.R., Humphreys, E.R. & Bubier, J. (2007) Contemporary carbon balance and late Holocene carbon accumulation in a northern peatland. *Global Change Biology*, 13(2), 397–411.

Schrier-Uijl, A.P., Kroon, P.S., Hendriks, D.M.D., Hensen, A., Van Huissteden, J., Berendse, F. & Veenendaal, E.M. (2014) Agricultural peatlands: towards a greenhouse gas sink - a synthesis of a Dutch landscape study. *Biogeosciences*, 11(16), 4559–4576.

Schrier-Uijl, A.P., Kroon, P.S., Hensen, A., Leffelaar, P.A., Berendse, F. & Veenendaal, E.M. (2010) Comparison of chamber and eddy covariance-based $CO_2$ and $CH_4$ emission estimates in a heterogeneous grass ecosystem on peat. *Agricultural and Forest Meteorology*, 150(6), 825–831.

Shannon, R. & White, J. (1994) A three-year study of controls on methane emissions from two Michigan peatlands. *Biogeochemistry*, 27(1), 35–60.

Shurpali, N.J., Verma, S.B., Kim, J. & Arkebauer, T.J. (1995) Carbon dioxide exchange in a peatland ecosystem. *Journal of Geophysical Research: Atmospheres*, 100(D7), 14319–14326.

Smith, K.A., Ball, T., Conen, F., Dobbie, K.E., Massheder, J. & Rey, A. (2003) Exchange of greenhouse gases between soil and atmosphere: interactions of soil physical factors and biological processes. *European Journal of Soil Science*, 54(4), 779–791.

Sonnentag, O., Van Der Kamp, G., Barr, A.G. & Chen, J.M. (2010) On the relationship between water table depth and water vapor and carbon dioxide fluxes in a minerotrophic fen. *Global Change Biology*, 16(6), 1762–1776.

Strack, M., Keith, A.M. & Xu, B. (2014) Growing season carbon dioxide and methane exchange at a restored peatland on the Western Boreal Plain. *Ecological Engineering*, 64, 231–239.

Strack, M. & Waddington, J.M. (2012) Effects of peat extraction and restoration on greenhouse gas exchange from Canadian peatlands. In: Vitt, D. & Bhatti, J. (eds.) *Restoration and Reclamation of Boreal Ecosystems*, Cambridge University Press, 386–404.

Strack, M. & Zuback, Y.C.A. (2013) Annual carbon balance of a peatland 10 yr following restoration. *Biogeosciences*, 10, 2885–2896.

Sulman, B.N., Desai, A.R., Cook, B.D., Saliendra, N. & Mackay, D.S. (2009) Contrasting carbon dioxide fluxes between a drying shrub wetland in Northern Wisconsin, USA, and nearby forests. *Biogeosciences*, 6(6), 1115–1126.

Sulman, B.N., Desai, A.R., Saliendra, N.Z., Lafleur, P.M., Flanagan, L.B., Sonnentag, O., Mackay, D.S., Barr, A.G. & van der Kamp, G. (2010) $CO_2$ fluxes at northern fens and bogs have opposite responses to inter-annual fluctuations in water table. *Geophysical Research Letters*, 37(19), L19702.

Syed, K.H., Flanagan, L.B., Carlson, P.J., Glenn, A.J. & Van Gaalen, K.E. (2006) Environmental control of net ecosystem $CO_2$ exchange in a treed, moderately rich fen in northern Alberta. *Agricultural and Forest Meteorology*, 140(1–4), 97–114.

Teh, Y., Silver, W., Sonnentag, O., Detto, M., Kelly, M. & Baldocchi, D. (2011) Large greenhouse gas emissions from a temperate peatland pasture. *Ecosystems*, 14(2), 311–325.

Treat, C.C., Bubier, J.L., Varner, R.K. & Crill, P.M. (2007) Timescale dependence of environmental and plant-mediated controls on $CH_4$ flux in a temperate fen. *Journal of Geophysical Research: Biogeosciences*, 112(G1), G01014.

Tuittila E.-S., Komulainen V.M., Vasander, H. & Laine, J. (1999) Restored cut-away peatland as a sink for atmospheric $CO_2$. *Oecologia*, 120(4), 563–574.

Turetsky, M.R., Kotowska, A., Bubier, J., Dise, N.B., Crill, P., Hornibrook, E.R.C., Minkkinen, K., Moore, T.R., Myers-Smith, I.H., Nykänen, H., Olefeldt, D., Rinne, J., Saarnio, S., Shurpali, N., Tuittila, E.-S., Waddington, J.M., White, J.R., Wickland, K.P. & Wilmking, M. (2014) A synthesis of methane emissions from 71 northern, temperate, and subtropical wetlands. *Global Change Biology*, 20, 2183–2197.

UNDP, UNEP, World Bank & WRI (2000) *World Resources 2000–2001: People and Ecosystems; The Fraying Web of Life*. World Resources Institute, Washington DC, 28 pp. Online at: http://www.wri.org/sites/default/files/pdf/world_resources_2000–2001_summary.pdf

van der Nat, F.-J.W.A. & Middelburg, J.J. (1998) Seasonal variation in methane oxidation by the rhizosphere of *Phragmites australis* and *Scirpus lacustris*. *Aquatic Botany*, 61, 95–110.

Vasander, H. & Kettunen, A. (2006) Carbon in boreal peatlands. In: Wieder, R.K. & Vitt, D.H. (eds.) *Boreal Peatland Ecosystems*. Ecological Studies 188, Springer-Verlag, Heidelberg, Germany, 165–194.

Waddington, J.M. & Day, S.M. (2007) Methane emissions from a peatland following restoration. *Journal of Geophysical Research: Biogeosciences*, 112(G3), G03018.

Waddington, J.M. & Price, J.S. (2000) Effect of peatland drainage, harvesting, and restoration on atmospheric water and carbon exchange. *Physical Geography*, 21(5), 433–451.

Waddington, J.M., Roulet N.T. & Swanson, R.V. (1996) Water table control of $CH_4$ emission enhancement by vascular plants in boreal peatlands. *Journal of Geophysical Research*, 101(D17), 22775–22785.

Waddington, J.M., Strack, M. & Greenwood, M.J. (2010) Toward restoring the net carbon sink function of degraded peatlands: Short-term response in $CO_2$ exchange to ecosystem-scale restoration. *Journal of Geophysical Research: Biogeosciences*, 115(G1), G01008.

Webb, E.K., Pearman, G.I. & Leuning, R. (1980) Correction of flux measurements for density effects due to heat and water vapour transfer. *Quarterly Journal of the Royal Meteorological Society*, 106(447), 85–100.

Wilson, D., Blain, D., Couwenberg, J., Evans, C.D., Murdiyarso, D., Page, S. Renou-Wilson, F., Rieley, J., Sirin, A., Strack, M., & Tuittila. E.-S. (2016) Greenhouse gas emission factors associated with rewetting of organic soils. *Mires and Peat*, 17(04) (in press).

Yu, Z., Loisel, J., Brosseau, D.P., Beilman, D.W. & Hunt, S.J. (2010) Global peatland dynamics since the Last Glacial Maximum. *Geophysical Research Letters*, 37(13), L13402.

*Submitted 06 Oct 2015, final revision 26 Jan 2016*
*Editor: David Wilson*

---

Author for correspondence:
Dr Andreas Christen, Department of Geography / Atmospheric Science Program, Department of Geography, The University of British Colombia, Vancouver Campus, 1984 West Mall, Vancouver, BC Canada V6T 1Z2.
Tel: +1 604 822 6620; Fax: +1 604 822 6150; E-mail: andreas.christen@ubc.ca