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Annual greenhouse gas budget for a bog ecosystem undergoing restoration by rewetting

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Abstract. Many peatlands have been drained and harvested for peat mining, which has turned them from carbon (C) sinks into C emitters. Rewetting of disturbed peatlands facilitates their ecological recovery, and may help them revert to carbon dioxide (CO_2) sinks. However, rewetting may also cause substantial emissions of the more potent greenhouse gas (GHG) methane (CH_4). Our knowledge on the exchange of CO_2 and CH_4 following rewetting during restoration of disturbed peatlands is currently limited. This study quantifies annual fluxes of CO_2 and CH_4 in a disturbed and rewetted area located in the Burns Bog Ecological Conservancy Area in Delta, BC, Canada. Burns Bog is recognized as the largest raised bog ecosystem on North America's West Coast. Burns Bog was substantially reduced in size and degraded by peat mining and agriculture. Since 2005, the bog has been declared a conservancy area, with restoration efforts focusing on rewetting disturbed ecosystems to recover *Sphagnum* and suppress fires. Using the eddy-covariance (EC) technique, we measured year-round (16th June 2015 to 15th June 2016) turbulent fluxes of CO_2 and CH_4 from a tower platform in an area rewetted for the last 8 years. The study area, dominated by sedges and *Sphagnum*, experienced a varying water table position that ranged between 7.7 (inundation) and -26.5 cm from the surface during the study year. The annual CO_2 budget of the rewetted area was -179 g CO_2-C m^{-2} year^{-1} (CO_2 sink) and the annual CH_4 budget was 16 g CH_4-C m^{-2} year^{-1} (CH_4 source). Gross ecosystem productivity (GEP) exceeded ecosystem respiration (R_e) during summer months (June-August), causing a net CO_2 uptake. In summer, high CH_4 emissions (121 mg CH_4-C m^{-2} day^{-1}) were measured. In winter (December-February), while roughly equal magnitudes of GEP and R_e made the study area CO_2 neutral, very low CH_4 emissions (9 mg CH_4-C m^{-2} day^{-1}) were observed. The key environmental factors controlling the seasonality of these exchanges were downwelling photosynthetically active radiation and 5-cm soil temperature. It appears that the high water table caused by ditch blocking which suppresses R_e. With low temperatures in winter, CH_4 emission was more suppressed than R_e. Annual net GHG flux from CO_2 and CH_4 expressed in terms of CO_2 equivalents (CO_2e) during the study period totaled to -55 g CO_2e m^{-2} year^{-1} (net CO_2e sink) and 1147 g CO_2e m^{-2} year^{-1} (net CO_2e source) by using 100-year and 20-year global warming potential

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values, respectively. Consequently, the ecosystem was almost CO_2e neutral during the study period expressed on a 100-year time horizon but was a significant CO_2e source on a 20-year time horizon.

1 Introduction

Wetland ecosystems play a disproportionately large role in the global carbon (C) cycle compared to the surface area they occupy. Wetlands cover only 6%–7% of the Earth's surface (Lehner and Döll, 2004), but they act as a major sink for the long-term storage of C by sequestering carbon dioxide (CO_2) from the atmosphere. For example, strong C sinks (-621 and -597 g CO_2-C m^{-2} $year^{-1}$) were found for temperate wetlands in Ontario, Canada and Siberia, respectively (den Hartog et al., 1994; Schulze et al., 1999). Other wetlands around the world sequester from -146 to -266 g CO_2-C m^{-2} $year^{-1}$ (Lafleur et al., 2001; Pihlatie et al., 2010; Shurpali et al., 1995). C storage in wetlands has been estimated to be up to 450 Gt C or approximately 20% of the total C storage in the terrestrial biosphere (Gorham, 1991; Maltby and Immirzi, 1993). However, wetlands emit significant quantities methane (CH_4), a powerful GHG, due to anaerobic microbial decomposition (Aurela et al., 2001; Rinne et al., 2007). CH_4 emissions from wetlands are responsible for 30% of all global CH_4 emissions (Ciais et al., 2013). Peatlands are the most widespread of all wetland types in the world, representing 50 to 70% of global wetlands (Mundava, 2011). Their dynamics have played an important role in the global C cycle during the Holocene period (Gorham, 1991; Yu, 2011), and it has been shown that including peatlands in the modelling and analysis of the global C cycle to mitigate the changes in other C reservoirs is highly relevant (Brovkin et al., 2002; Kleinen et al., 2010; Menviel and Joos, 2012).

Many peatlands have been harvested and continue to be disturbed by the extraction of peat for horticultural use. In the case of Burns Bog, peat was also used for fire bombs during World War II (Cowen, 2015). Generally, during harvesting, the surface vegetation is removed, and then wetlands are drained by a network of ditches (Price and Waddington, 2000; Waddington and Roulet, 2000). When no longer economical, many harvested peatlands are abandoned and kept at artificially low water tables due to the drainage ditches. This environmental condition limits the disturbed and abandoned peatlands ability to return to their prior state. Drainage results in increased oxidation in peat soils, which then can become a strong source of CO_2 (Langeveld et al., 1997; Petrescu et al., 2015; Tapio-Biström et al., 2012). Additionally, degraded peat an increased fire risk, which can produce significant CO_2 emissions (Gaveau et al., 2014; Page et al., 2002; van der Werf et al., 2004). These consequences could be worse if nothing is done after the peat extraction. Therefore, and for reasons of conservation ecology (unique habitat), disturbed peatlands may be restored.

Restoration efforts typically rely on elevating the water table and managing vegetation. The water table depth and the amount of vegetation are the most important factors affecting land-atmosphere C exchange. Rewetting by ditch blocking can have an immediate impact on the C exchange between the peatland surface and the atmosphere (Limpens et al., 2008). Rewetting has strong direct and indirect effects on CO_2 and CH_4 fluxes. Raising the water level has been found to suppress the CO_2 efflux from the soil and result in an increase in net CO_2 uptake by native bog vegetation (Komulainen et al., 1999).

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CH_4 emissions from rewetted sections in a bog in Finland were three times higher than the release from the disturbed and dry area (Tuittila et al., 2000). Another study found similar rates of CH_4 production in disturbed and restored wetlands in the southern United States (Schipper and Reddy, 1994). Re-vegetation of degraded peat leads to faster re-establishment of peat formation that can have significant effects on C exchange. However, the increased above- and below-ground biomass of plants and litter enhances organic matter oxidation, which raises CO_2 emissions (Finér and Laine, 1998; Minkkinen and Laine, 1998). In another study, re-establishing the conditions permitting peat formation also initially increased CH_4 emission, but the C exchange did not reach the level of seasonal emissions from pristine peatlands (Crill et al., 1992; Dise et al., 1993; Shannon and White, 1994).

Very few studies provide continuous, long-term measurements to determine how restored and rewetted peatland ecosystems recover in terms of their productivity and GHG exchange. It remains unclear when, or even if, restored peatland ecosystems could show a similar magnitude of C fluxes as in pristine (undisturbed) peatland ecosystems. Furthermore, most investigation focusing on GHG exchange of restored peatlands only measured CO_2 and/or CH_4 fluxes during short periods, e.g. the growing season. There are few studies that measured continuously and year-round fluxes (Anderson et al., 2016; Järveoja et al., 2016; Knox et al., 2015; Richards and Craft, 2015; Strack and Zuback, 2013), relying instead on sporadic, or repeating chamber measurements, which are difficult to upscale to annual totals.

In this study, we a) quantified seasonal and annual CO_2 and CH_4 fluxes, using the eddy covariance (EC) technique, in a disturbed ecosystem that is representative of areas subject to recent restoration efforts (ditch blocking for the last 8 years), b) identified key environmental controls and their effects on CO_2 and CH_4 fluxes, and c) quantified whether the study ecosystem is net source or sink of C and its net climate forcing at different time scales by considering GWPs of CO_2 and CH_4.

2 Study area

Burns Bog in Delta, BC, on Canada's Pacific Coast, is part of a remnant peatland ecosystem that is recognized as the largest raised bog ecosystem on North America's west coast. During the last century, it was significantly disturbed as a result of it being used for housing, peat mining and agriculture (MetroVancouver, 2007). The Burns Bog Ecological Conservancy Area (BBECA) was established in 2005 to conserve this large coastal raised bog and restore ecological integrity to the greatest extent possible. Christen et al. (2016) measured summertime CO_2 and CH_4 exchanges using primarily chamber systems in several plots representative of disturbed areas of the BBECA, where some plots were rewetted and others were not. The study found substantial emissions of CH_4 primarily in recently rewetted plots, with highest emissions found under a high water table. Nevertheless, a significant spatial and temporal variability was found between and within plots. In order to constrain these emission estimates, it was suggested to extend the year-round monitoring of CO_2 and CH_4 exchanges using EC technique to provide spatially more representative fluxes at a recently rewetted plot.

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The current study site is located in a harvested, disturbed, and rewetted area in the centre of the BBECA (122°59'05.87"W, 49°07'47.20"N, WGS-84) with dimensions of 400 m by 250 m. The field is surrounded by a windbreak to the west and an abandoned (now blocked) drainage ditch to the north (see supplementary material, Fig. S1 and S2). The study area was harvested between 1957 and 1963 using the Atkins-Durbrow Hydropeat method to remove the peat (Heathwaite and Göttlich, 1993). In 2007, the study site was rewetted via ditch-blocking using dams built with plywood and using wooden stakes as bracing (Howie et al., 2009). Following rewetting, water table height (WTH) in the study area fluctuates between 30 cm above ground and 20 cm below ground over the year. In all years since rewetting started in 2007, water table positions were lower in late summer and early fall and high all winter and spring. WTH decreases steadily between June and September. In September and October, the water table rises due to the increase in precipitation and the reduced evapotranspiration as a consequence of senescence. The depth of peat at the study site is 5.83 m. A silty clay layer is located below the peat layer (Chestnutt, 2015). The plant communities in the study ecosystem are dominated by *Sphagnum spp.* and *Rhynchospora alba*. The average height of the vegetation during the growing season is about 0.3 m (Madrone Consultants Ltd., 1999). Plants are separated by shallow open water pools, some of them populated by algae developing. Birch trees are dispersed and appear to be growing on the remnants of baulks but none of them was taller 2 m. Sphagnum covers over 25% of the surface inside the study area (Hebda et al., 2000). The area of the open water ponds was estimated to be about 20% of the surface in summer by aerial photo.

3 Materials and methods

3.1 Climate measurements

Weather variables were continuously measured in order to determine climatic controls of CO_2 and CH_4 fluxes. Four components of radiation (shortwave/longwave, incoming and outgoing) were continuously measured by a four-component net radiometer (CNR1, Kipp and Zonen, Delft, Holland) on top of the tower. Two quantum sensors (LI-190, LI-COR Inc., Lincoln, NE, USA) measured incoming and outgoing photosynthetically active radiation (PAR). Precipitation was measured with an unheated tipping bucket rain gauge (TR-525M, Texas Electronics, Dallas, TX, USA) at 1 m height, 10 m north of the tower. Air temperature (T_a) and relative humidity (RH, HMP-35 A, Vaisala, Finland) were measured at the heights of 2.0 m and 0.3 m, and soil thermocouples (type T) were recording soil/water temperatures at the depths of 0.05, 0.10 and 0.50 m. A pressure transducer (CS400, CSI) was installed on July 28th 2015 in an observation well west of the tower to continuously measure WTH for the remainder of the study period.

3.2 Eddy-covariance measurements

Over the entire annual study period, from 16th June 2015 to 15th June 2016, a long-term eddy-covariance system (EC-1) was operated on a floating scaffold tower (Fig. 1) at a height of 1.8 m (facing south). The EC-1 system consisted of an ultrasonic anemometer-thermometer (CSAT-3, Campbell Scientific Inc. (CSI)) and an open-path CO_2/H_2O infrared gas analyzer

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(IRGA, LI-7500, LI-COR Inc.). The path separation between CSAT-3 and LI-7500 was 5 cm. The CSAT-3 measured three-dimensional wind (*u, v, w*, in m s^{-1}) and sonic temperature (T_s, in ºC) at 60 Hz and output data at 10 Hz. The IRGA measured water vapor density (ρ_v) and CO_2 density (ρ_c) at 10 Hz. The 10-Hz data from both instruments were sampled on a data logger (CR1000, CSI) and processed fluxes of CO_2 (F_c) were calculated over 30 min blocks following the procedures documented in Crawford et al. (2013).

An additional, independent EC system (EC-2) was added on June 10th 2015 to measure CH_4 fluxes. The EC-2 system was also located at a height of 1.8 m, 1.8 m to the west of EC-1, and faced south (Fig. 1). EC-2 consisted of a similar ultrasonic anemometer-thermometer (CSAT-3, CSI, 20 Hz), an enclosed-path H_2O/CO_2 IRGA (LI-7200, LI-COR Inc. 20 Hz) and an open-path gas analyzer to measure the partial density of CH_4 (ρ_m) (LI-7700, LI-COR Inc., 20 Hz). The northward-separation of LI-7200 was 20 cm. The northward-separation of LI-7700 was 40 cm and eastward-separation of LI-7700 was 20 cm. Data from EC-2 were collected by an analyzer interface unit (LI-7550, LI-COR Inc.) and processed on-site. Fluxes of CH_4 (F_m) were processed in advanced mode using EddyPro® (V6.1.0, LI-COR Inc.) with a missing sample allowance of 30%. F_m data were quality checked using the flagging system proposed by Mauder and Foken (2004).

3.3 Gap filling algorithms

Some gaps in climate and flux measurements are unavoidable due to challenging weather and low-light situations (the station was solar powered), and need to be filled in for estimating seasonal and annual fluxes. Gaps in climate data (<1% of a year) were filled using measurements at nearby climate stations as documented in Lee et al. (2016). Small gaps (<60 minutes) of missing CO2 and CH4 fluxes were filled by linear interpolation. Longer gaps were filled using empirical relationships between CO_2 or CH_4 fluxes and environmental variables. Two-year (from July 2014 to June 2016) of measurements of CO_2 fluxes were used for modelling R_e and GEP to achieve better statistical relationships. Since there were two EC systems running with redundant fluxes of CO_2, the sensitivity of different combinations of data (EC-1 vs. EC-2 or using an average of the two) have been explored in Lee et al. (2016). For the data presented in this study, CO_2 fluxes, *H*, *LE* from EC-1 and CH_4 fluxes EC-2 were used. Valid data from EC-1 was obtained for 59% of the year (after quality control). Valid data from EC-2, which was restricted by power availability, was 32% of the year (after quality control).

3.3.1 Gap filling of CO_2 flux data

For gaps longer than 2 hours in CO_2 fluxes, the CO_2 flux (e.g., net ecosystem exchange, NEE) was modelled as the difference between ecosystem respiration (R_e) and gross ecosystem photosynthesis (GEP) i.e. $\mathrm{NEE} = R_e - \mathrm{GEP}$. Nocturnal NEE values were R_e as there is no photosynthesis (GEP) at night.

R_e was modelled based on soil temperature at the 5-cm depth ($T_{s,5cm}$) using a logistic fit (Neter et al., 1988):

$$R_e = \frac{1}{r_1 r_2^{T_{s,5cm}} + r_3} \tag{1}$$

A comparable logistic function was proposed and used by FLUXNET Canada (Barr et al., 2002; Kljun et al., 2006). In this study, we used this logistic model available in IDL (version 8.5.1, Exelis Visual Information Solutions, Boulder, Colorado). r_1, r_2, and $r_3$are empirical parameters; $r_1$controls the slope of exponential phase; $r_2$decides where the transitional phase starts; and $r_3$determines the height of plateau phase. The empirical parameters r_1, r_2, and r_3 were determined separately for each day of the year, using a moving window of 120 days (60 days into past and 60 days into future) based on all measured nighttime data from 2014 to 2016 when friction velocity was higher than 0.08 m s^{-1}. Lee (2016) determined the effect of using different window sizes (60, 90, 120 and full year) on the annual modelled and gap-filled R_e and showed that a moving window size of 120 days was least sensitive to errors while still allowing for seasonal changes. However, sensitivity of choosing different window sizes on gap filled R_e was small, varying the annual value between 221 and 229 g C m^{-2} $year^{-1}$.

GEP was modelled using the photosynthetic light-response curves (Ögren and Evans, 1993) based on photosynthetic photon flux density (PPFD in μmol m^{-2} s^{-1}):

$$\mathrm{GEP} = \frac{MQY \cdot \mathrm{PPFD} + P_M - ((MQY \cdot \mathrm{PPFD} + P_M)^2 - 4 \cdot C_v \cdot MQY \cdot \mathrm{PPFD} \cdot P_M)^{0.5}}{2 \cdot C_v} \quad (2)$$

Maximum photosynthetic rate at light saturation (P_M) and maximum quantum yield (MQY) are fitted parameters with GEP estimated as measured daytime NEE minus daytime R_e calculated using Eq. 1. Convexity (C_v) was fixed at 0.7 (Farquhar et al., 1980). The time-varying parameters MQY and P_M were fitted separately for each day, using a moving window of 90 days using all data from 2014 to 2016 when friction velocity was higher than 0.08 m s^{-1}. The sensitivity of window size on gap filled GEP was small, resulting in annual value to vary between 385 and 415 g C m^{-2} $year^{-1}$.

3.3.2 Gap filling of CH_4 flux data

CH_4 fluxes with quality flags 0 and 1 according to Mauder and Foken (2004) were plotted against all related variables including WTH, θ_w, T_a, and $T_{s,5cm}$. Since the main control was $T_{s,5cm}$, it was used to build a model to fill the gaps in CH_4 fluxes:

$$F_m = ae^{bT_{s,5cm}} \quad (3)$$

where F_m is the CH_4 flux, $T_{s,5cm}$ is the soil temperature at the 5 cm depth, and a and b are empirical parameters for the annual relationship.

3.4 Calculating CO_2e

The combined effect all long-lived greenhouse gases was compared for CO_2 and CH_4 by converting the molar fluxes of CO_2 and CH_4 into time-integrated radiative forcing (e.g. global warming potential, GWP) expressed on a mass basis in terms of CO_2 equivalents (g CO_2e m^{-2} s^{-1}) as follows:

$$CO_2\text{e (g)} = m_{CO_2}F_{CO_2} + GWP_{CH_4}m_{CH_4}F_{CH_4} \quad (4)$$

GWP_{CH_4} is the mass-based GWP for the CH_4 (g g^{-1}), m_{CO_2} is the molecular mass of CO_2 (g mol^{-1}), and m_{CH_4} is the molecular mass of CH_4 (g mol^{-1}). In this study, a 100-year GWP of CH_4 of 28, and 20-year GWP of CH_4 of 84, were used respectively (IPCC, 2014). N_2O fluxes have been neglected in this study because previous chamber-based measurements during the growing season found no significant emissions or uptake of N_2O in all study plots in the BBECA (Christen et al., 2016).

4 Results and Discussion

4.1 Weather

During the study period (June 16th 2015 to June 15th 2016), the site experienced an annual average T_a (2 m height) of 11.3 ºC. Mean monthly T_a ranged between 4.4 (Jan 2016) and 19.3 ºC (Jul 2015). The study site received a total annual precipitation of 1061.7 mm, of which 16% (173.4 mm) fell during the warm half year (Apr-Sep) and 84% (888.3 mm) during the cold half year (Oct-Mar). There was no lasting snow cover during the study year. However, the surface was frozen over ten days in January 2016, with an ice thickness of up to 5 cm.

Winds at this site were often influenced by a sea-land breeze circulation. Under sea-breeze situations, wind mainly came from the south (40% of all cases). Sometimes, however, the sea-land breeze blew from the west, primarily between 17:00 and 19:00 PST. The wind direction on average turned to east during the nighttime (land-breeze), and generally at night, the winds were weaker.

4.2 Surface conditions

4.2.1 Turbulent flux footprints

Cumulative turbulent source areas were calculated using the analytical turbulent source area (turbulent footprint) model from Kormann and Meixner (Kormann and Meixner, 2001) following the procedure outlined in Christen et al. (2011). The 80% contour line (enclosing 80% of the cumulative probability for a unit source) was entirely inside the field in spring and summer. It reached beyond the ditches at the north side in fall and winter. Unstable conditions during daytime allowed for a more constrained footprint surrounding the tower. Stable conditions at night led to larger footprints, primarily from East. The cumulative footprint for each of the four seasons for the EC-1 overlaid on the satellite image of the site are documented in Fig. S1 (supplementary material).

4.2.2 Vegetation cover and water table changes

Mosses and sedges started to grow in March and grasses grew up to a maximum of 0.3 m height in summer. In summer, vegetation covered almost the entire study area of the surface, including ponds (some with algae), so the surface was less patchy in summer compared to other seasons, when standing water ponds were intermixed with vegetation in fall, winter and spring (see supplementary material, Fig. S2).

Winter was the wettest season when WTH was mostly above the bare soil (reference surface). The highest water table position was 7.7 cm above the reference surface in December. In the dry season, the water table position dropped to 26.5 cm beneath the bog surface in August. The WTH decreased in spring, and dry hummocks could be seen from April to September. The water table started to rise above the surface after receiving the fall precipitation. The study site was flooded in winter during the study year.

4.3 CO_2 exchange

4.3.1 Annual, seasonal and monthly NEE, R_e and GEP

Overall, the study area was a CO_2 sink in spring (MAM, -1.10 g C m^{-2} day^{-1}) and in summer (JJA, -0.82 g C m^{-2} day^{-1}). Net CO_2 fluxes were near zero in fall (SON, +0.03 g C m^{-2} day^{-1}) and winter (DJF, -0.07 g C m^{-2} day^{-1}). Over the entire year, the annual CO_2-C budget (i.e., NEE) was -179 g C m^{-2} yr^{-1}. Almost in each month of the calendar year, the site was a weak sink for CO_2 except in October, November and December (Fig. 2, Table 1). Monthly net fluxes of CO_2 (NEE) ranged from +1.77 g C m^{-2} month^{-1} in November 2015 to -56.20 g C m^{-2} month^{-1} in May 2016.

The annual R_e and GEP during the study year were 236 and 415 g C m^{-2} yr^{-1}, respectively. The relative changes in R_e and GEP were closely linked to the seasonality of the plant phenology. Based on GEP trends, we can divide the study period into three segments, ‘winter’ (Oct-Mar), ‘early growing season’ (Apr-Jun), and ‘late growing season (Jul-Sep). The rising temperature triggered growth in the early growing season (GEP = 59.73 g C m^{-2} month^{-1}), while the later growing season had limited growth (GEP = 25.08 g C m^{-2} month^{-1}). Winter had lowest productivity (GEP = 7.58 g C m^{-2} month^{-1}) (Table 1). Despite a large seasonal amplitude in monthly GEP, R_e showed less variability over the year. The highest increasing rate of NEE and the highest magnitude of NEE both occurred in May during the early growing season (Fig. 2). This was caused by the onset of R_e being delayed compared to GEP, resulting in the greatest imbalance between respiratory and assimilatory fluxes in May.

Table 2 compares annual NEE, R_e and GEP at the study site to Fluxnet sites over other land covers in the same region that experienced similar climate forcings, although from different years. An unmanaged grassland site 15 km to the west of the study area in the Fraser River Delta (Westham Island, Delta, BC, Crawford et al., 2013) had about 1.3 times higher NEE than this rewetted area. Annual R_e and GEP values at this grassland site were higher than the study site by a factor of 5.2 and 3.5. A mature 55-year-old Douglas-fir forest on Vancouver Island (200 km NW of the study area; Krishnan et al., 2009) showed an NEE of 1.8 times higher than the study area. The R_e and GEP were even higher by factors of 7.8 and 5.2, respectively. A young forest plantation (Buckley Bay, 150 km W of the study area; Krishnan et al., 2009), which was a weak C source, had R_e and GEP of six- and three-fold higher than the study site, respectively. Compared to these other sites under similar climatic conditions, the rewetted area of the bog was not an ecosystem of high productivity but one with considerably limited R_e that permits more efficient CO_2 sequestration (-NEE is 43 % of GEP, as opposed to 15% for the unmanaged grassland site and mature forest).

4.3.2 Diurnal variability in CO_2 fluxes

The seasonally-changing diurnal course of gap-filled NEE with isopleths over time of day and year is shown in Fig. 3. The daily maximum GEP changed seasonally, consequently the highest NEE was observed during midday between May and July (-3.5 µmol m^{-2} s^{-1}). During nighttime, R_e was less varying with season, and on average was ≤ 1 µmol m^{-2} s^{-1} for most of the study period.

4.3.3 Ecosystem respiration

Figure 4 shows the relationship between nighttime R_e and $T_{s,5cm}$ using the data for the entire study period. R_e increased with increasing $T_{s,5cm}$ as expected, and annually followed a logistic curve rather than an exponential relationship. R_e response curves were also calculated every two months (see supplementary material, Fig. S3). R_e showed different curves depending on season. In winter, R_e varied little with $T_{s,5cm}$ and was close to zero. From February to May, the relationship became closer to logistic. In June and July, the fitted curve stayed at 1 µmol m^{-2} s^{-1} because $T_{s,5cm}$ remained above 15 ºC. The study area had the highest R_e in these two months. In fall, R_e curves were closer to an exponential relationship, which could be due in part to leaf senescence (Shurpali et al., 2008). Decomposition of dead plant organic matter on the soil surface may have caused a higher R_e in fall compared to spring and winter at the same $T_{s,5cm}$. Another factor could be the WTH, which in fall was not high enough to suppress R_e as it did in winter (Juszczak et al., 2013). The differences between March and September at the same $T_{s,5cm}$ were up to 0.4 µmol m^{-2} s^{-1}.

Two other controls on R_e explored were air temperature (T_a) and WTH. T_a did have a similar impact on R_e as $T_{s,5cm}$ when T_a < 16ºC, but for warmer temperatures, T_a did not correlate with R_e. The explanation for this is that heterotrophic component of R_e depends on T_s, not the rapidly changing T_a (Davidson et al., 2002; Edwards, 1975; Lloyd and Taylor, 1994).

It is widely reported that in most terrestrial ecosystems, the activity of soil microbes is also governed by soil moisture status, having little activity when the soil is excessively dry or excessively wet. Accordingly, and like other wetlands, R_e was small when the water table was above the surface because this situation suppressed aerobic decomposition of peat (Rochefort et al., 2002; Weltzin et al., 2000). When the water table was below surface, R_e increased to near 1 µmol m^{-2} s^{-1} and became stable no matter how low the water table position was. This relationship was also found in many other peatlands (Bridgham et al., 2006; Ellis et al., 2009; Strack et al., 2006). There was no obvious relationship between θ_w (integrated from 0-30 cm depth) and R_e. R_e slightly decreased from 1.0 to 0.6 μmol m^{-2} s^{-1} when θ_w increased from 84% to 88%. Other than this range, θ_w had no more impact on R_e.

4.3.4 Gross ecosystem photosynthesis

Figure 5 shows the average light response curve, with half-hourly GEP as a function of PPFD. Due to different phenology over the year and the changes in solar altitude, light response curves were also calculated every two months (see supplementary material, Fig. S4). GEP reached a maximum in May with 92.63 g C m^{-2} $month^{-1}$, and a minimum of 2.79 g C m^{-2} $month^{-1}$ in December (Fig. 2, Table 1). GEP at light saturation reached roughly 5.09 μmol m^{-2} s^{-1} in summer, and remained below 2.49 μmol m^{-2} s^{-1} in winter, due to reduced leaf area, flooding, and lower temperatures. From March to May, GEP increased much more rapidly than R_e. In fall, GEP decreased faster than R_e. The magnitude of R_e already was close to GEP in the late August to make the study area become CO_2 neutral in late summer.

Other possible controls on GEP explored were T_a and WTH. To exclude the primary driver, PAR, here only data when PAR was between 300 and 500 μmol m^{-2} s^{-1} (light had no effect on GEP) were used. We found out there was the light-independent photosynthesis which occurs in the stoma depending on T_a (Calvin, 1962) in the study area. Between 0 and 10 ºC T_a, photosynthesis was low even when supplied by ample PAR due to low leaf area during that period. A rapid increase in GEP was found from 10 to 15 ºC. When T_a was higher than 15 ºC. WTH did not show any direct influence on GEP.

4.4 CH_4 exchange

4.4.1 Annual and seasonal CH_4 budgets

Overall, the study area was a source of CH_4 in each of the twelve months (Table 1). The annual CH_4-C budget was 16 g CH_4-C m^{-2} yr^{-1}. CH_4 emissions were close to zero in winter (8.7 mg CH_4-C m^{-2} day^{-1}). It was a weak CH_4 source in fall (21.5 mg CH_4-C m^{-2} day^{-1}) and spring (29.4 mg CH_4-C m^{-2} day^{-1}), and then became a significant source in summer (120.9 mg CH_4-C m^{-2} day^{-1}). Monthly emissions of CH_4 ranged from 66 (November) to 4436 (July) mg CH_4-C m^{-2} $month^{-1}$. CH_4 fluxes showed a seasonal pattern, which was linked to phenology and temperature. The rising T_a did not trigger CH_4 production immediately, and CH_4 fluxes remained low in April and May. But once the subsurface and water became warm enough, CH_4 emissions increased from to 1.5 to 3.0 g CH_4-C m^{-2} $month^{-1}$ in June (Table 1). CH_4 emissions reached the peak in July (4.4 g CH_4-C m^{-2} $month^{-1}$) and held similar magnitude (3.7 g CH_4-C m^{-2} $month^{-1}$) in August even though the T_a had dropped.

4.4.2 Diurnal variability in CH_4 fluxes

The ensemble diurnal courses of the gap-filled CH_4 fluxes (measured CH_4 emissions and gap-filled by modelled CH_4 fluxes) by the EC-2 system are shown in Fig. 6 from June 16th 2015 to June 15th 2016. Surprisingly, there was not much of a diurnal course observed for CH_4 fluxes. CH_4 was continuously emitted through day and night. Thermal effects such as recently

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reported by Poindexter et al., 2016 were not found. From January to March and October to December, the study site had constant CH_4 emissions of less than 50 nmol m^{-2} s^{-1}, and almost no diurnal variation was observed. July had the greatest CH_4 emissions, and the highest magnitude (>150 nmol m^{-2} s^{-1}) appeared in the evening (3 pm to 9 pm). This corresponded to the lagged effect to soil temperature.

4.5 CO_2e exchange

Figure 7a and 7b show CO_2 and CH_4 fluxes expressed in terms of CO_2e using 100-year and 20-year GWPs, respectively. Considering fluxes of both GHGs together, this rewetted area was annually near to CO_2e neutral at 100-year scale with a net uptake by CO_2 (-656 g CO_2e m^{-2} year^{-1}) nearly the same as CH_4 emissions (601 g CO_2e m^{-2} year^{-1}). On shorter time horizon of 20 years, the study area represented a significant net climatic forcing in CO_2e terms as the net uptake of CO_2 (-656 g CO_2e m^{-2} year^{-1}) was one-third that of CH_4 emissions (1803 g CO_2e m^{-2} year^{-1}). In late spring and early summer, the early onset of CO_2 sequestration in May and the time lag in CH_4 fluxes combined to represent a negative net GHG forcing, no matter which GWP time horizon was considered. The quick drop in CO_2 sequestration in August and September allowed the highest net GHG forcing to be observed at both time horizons in late summer. In short, the critical time period for both, CO_2 and CH_4 fluxes, was the growing season when magnitude of fluxes changed differently across the growing season. The results show that measurements made during a part of the growing season are not necessarily representative for the entire growing season or the year. Christen et al., 2016 found that CH_4 emissions exceeded CO_2 uptake by a factor of 50 using GWPs at 100-year time horizon in July and August in a recently rewetted areas of the BBECA. During spring and early summer (April and May), however, CO_2 uptake can exceed CH_4 emissions.

5 Conclusions

The study area, a rewetted plot in the BBECA undergoing ecological restoration, was a net CO_2 sink over the study period (-179 g CO_2-C m^{-2} year^{-1}). The study area was not a highly productive ecosystem (annual GEP = 415 g CO_2-C m^{-2} year^{-1}) but exhibited low R_e (annual R_e = 236 g CO_2-C m^{-2} year^{-1}), likely due to oxygen limitations. The annual CO_2 fluxes reported here from a restored and rewetted peatland are comparable with data reported from pristine temperate peatlands in temperate mid latitudes (Alm et al., 1997; Lafleur et al., 2001; Pihlatie et al., 2010; Shurpali et al., 1995). The study area sequestered less CO_2 than the few other restored wetlands reported in the literature (Anderson et al., 2016; Järveoja et al., 2016; Knox et al., 2015; Richards and Craft, 2015; Strack and Zuback, 2013). The major controls on CO_2 fluxes were PAR irradiance and $T_{s,5cm}$. The magnitude of PAR strongly controlled GEP, and the $T_{s,5cm}$ regulated R_e. WTH also had influence on R_e especially when the ecosystem was flooded.

Annual CH_4 emissions were 16 g CH_4-C m^{-2} year^{-1}, which is lower than those reported for other restored wetlands (Anderson et al., 2016; Knox et al., 2015). CH_4 emissions in summer months were 60 times stronger than in winter. The ditch blocking permitted anaerobic conditions with the water table within 30 cm of the surface throughout the year. Effects of changing WTH on CH_4 fluxes at the study area were not clearly apparent. $T_{s,5cm}$ explained CH_4 fluxes best (R^2 = 0.66) – although both $T_{s,5cm}$ and WTH changed seasonally.

In terms of the C balance, our results suggest that our study area in BBECA was a net C sink (-163 g C m^{-2} $year^{-1}$) during the 8th year following rewetting. These results are consistent with those of several disturbed peatlands that have become a net annual C sink after following restoration by rewetting (Karki et al., 2016; Schrier-Uijl et al., 2014; Wilson et al., 2013). In terms of net climate forcing of the system related to CO_2 and CH_4 fluxes expressed by GWPs, our results show that the ecosystem was almost CO_2e neutral (-55 g CO_2e m^{-2} $year^{-1}$) over a 100-year time horizon during the study period after a 7-year restoration. However, the rewetted area was a substantial net CO_2e source (1147 g CO_2e m^{-2} $year^{-1}$) on a 20-year time horizon due to the stronger GWP of CH_4 on shorter timescales.

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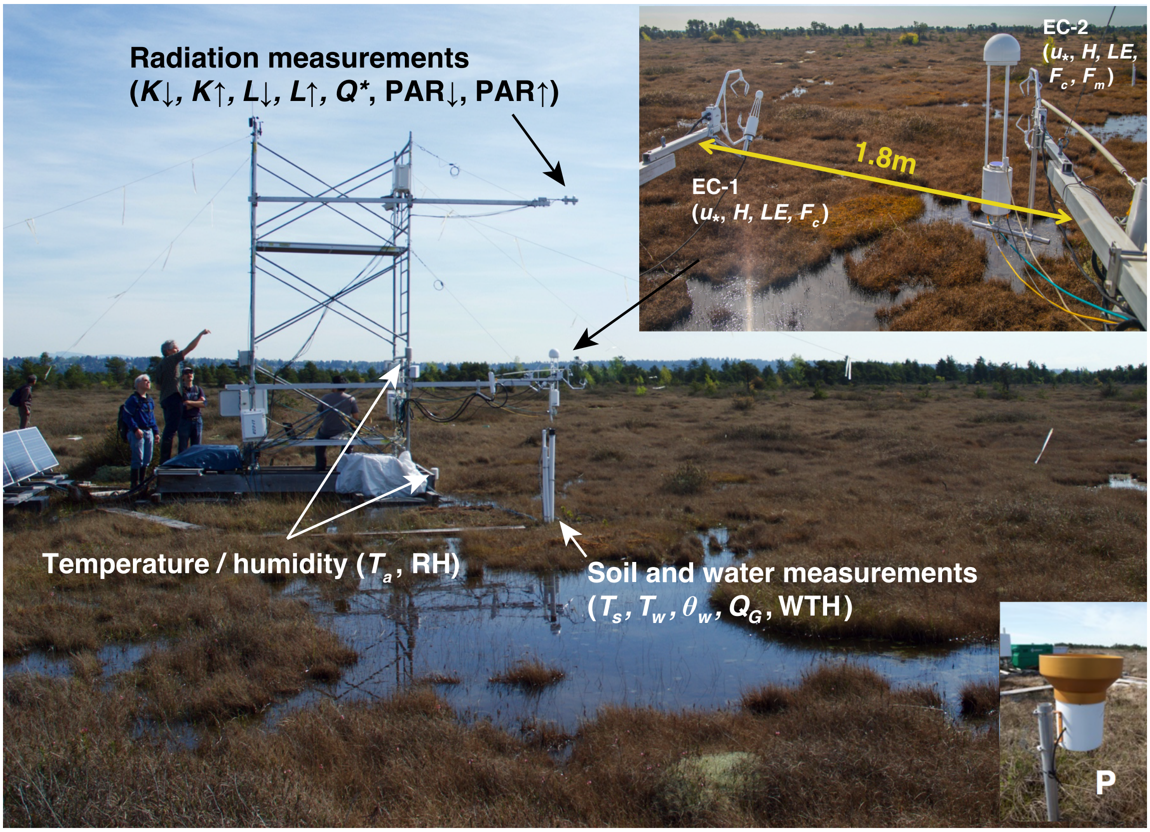

535 Figure 1: Flux tower on floating platform with EC-1 and EC-2 systems facing south and instruments that measured climate variables indicated (friction velocity (u_*), sensible heat flux (H), latent heat flux (LE), CO_2 flux (F_c), CH_4 flux (F_m), incoming shortwave radiation (K ↓), outgoing shortwave radiation (K ↑), incoming longwave radiation (L ↓), outgoing longwave radiation (L ↑), net all-wave radiation (Q*), incoming PAR (PAR ↓), outgoing PAR (PAR ↑), air temperature (T_a), relative humidity (RH), soil temperature (T_s), water temperature (T_w), soil water content (θ_w), soil heat flux (Q_G), water table
540 height (WTH), and precipitation (P)).

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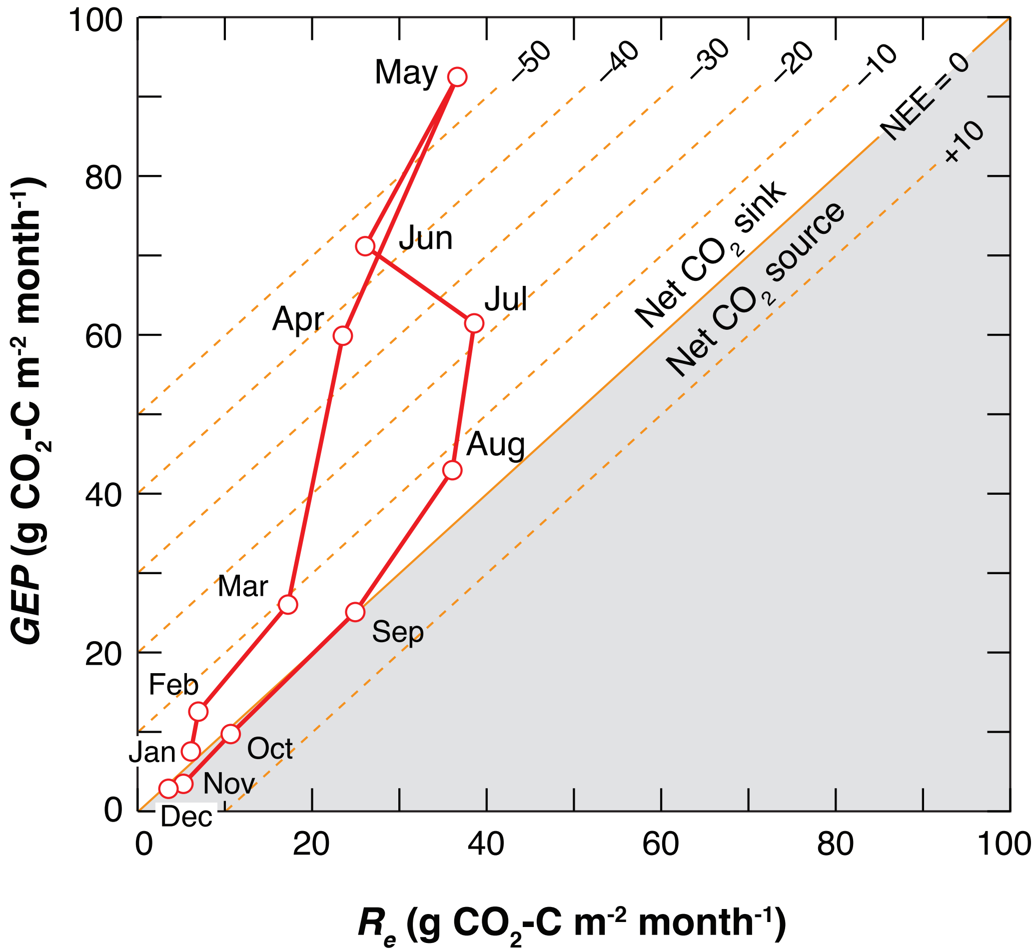

Figure 2: Monthly gap-filled R_e (x-axis) drawn against GEP (y-axis). The resulting NEE can be read off the diagonal lines. The thick 1:1 line shows carbon neutrality, while lines in the upper right are of increasingly negative NEE (uptake) and lines towards the lower right are positive NEE (net source).

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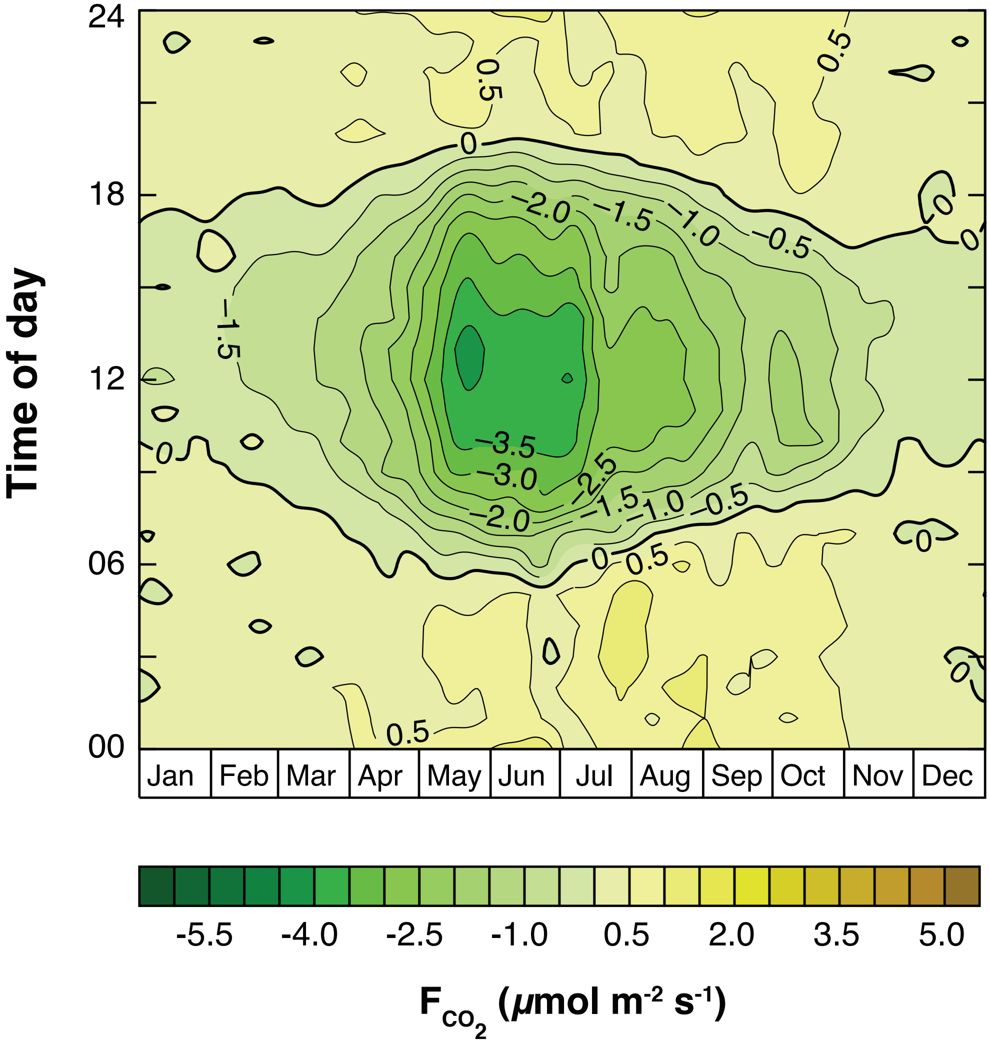

545 Figure 3: Isopleths of gap-filled NEE (net CO_2 fluxes) from the EC-1 system plotted as a composite in the study year. The graph uses a Gaussian filter of σ = 45 days (which conserves total NEE) to graphically smooth horizontal variations.

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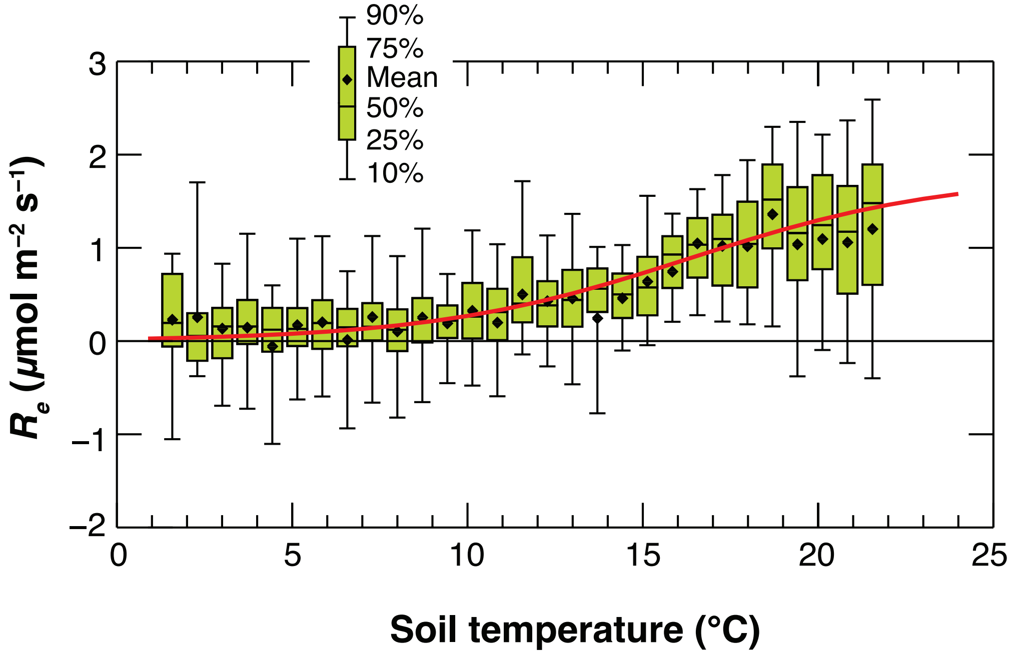

Figure 4: Relationship between R_e (nighttime 30-minute CO_2 flux measurements) and $T_{s,5cm}$ during the entire study period. The u_* threshold was 0.08 m s^{-1}. The fitted curve is a logistic relationship following Eq. 1. $T_{s,5cm}$ was binned for 32 classes from minimum of $T_{s,5cm}$ to maximum of $T_{s,5cm}$. See Fig. S3 in supplement for seasonal differences. Negative R_e values were caused by measurement uncertainties.

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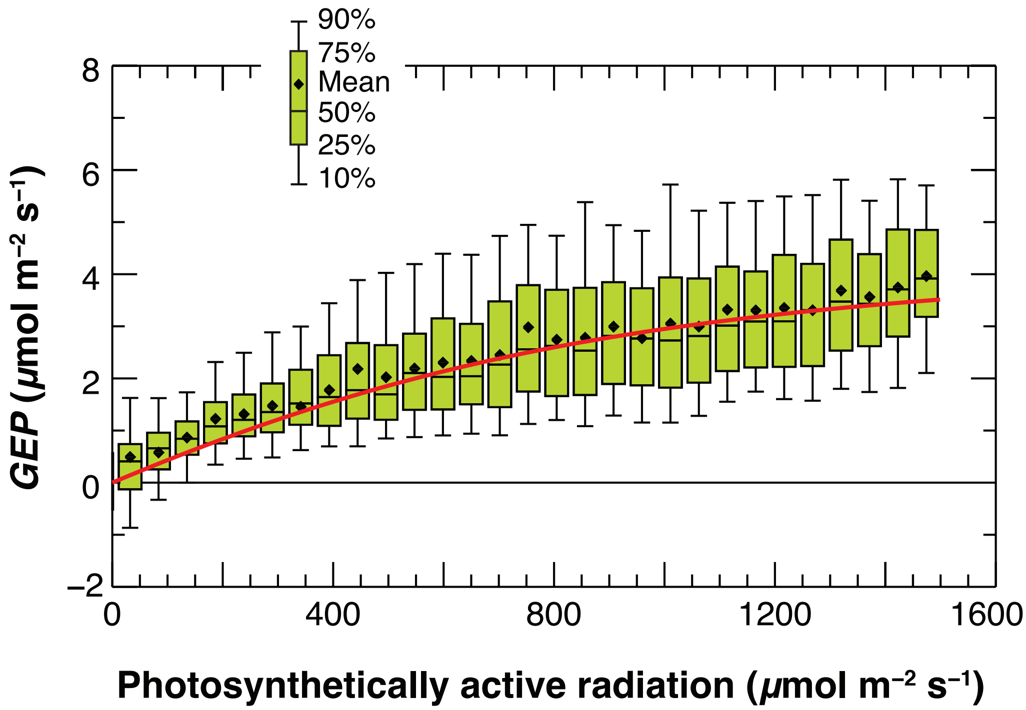

555 Figure 5: Annual light response curve determined from the daytime 30-minute NEE measurements and Eq. 1, i.e., GEP = R_e + -NEE. The curves are the best fit of the Eq. 2. PPFD was binned for 30 classes from 0 to 1500 µmol m^{-2} s^{-1}. Annual *MQY* was 4.00 mmol C mol^{-1} photons, P_M was 4.68 umol m^{-2} s^{-1}, and C_v was 0.7 (fixed).

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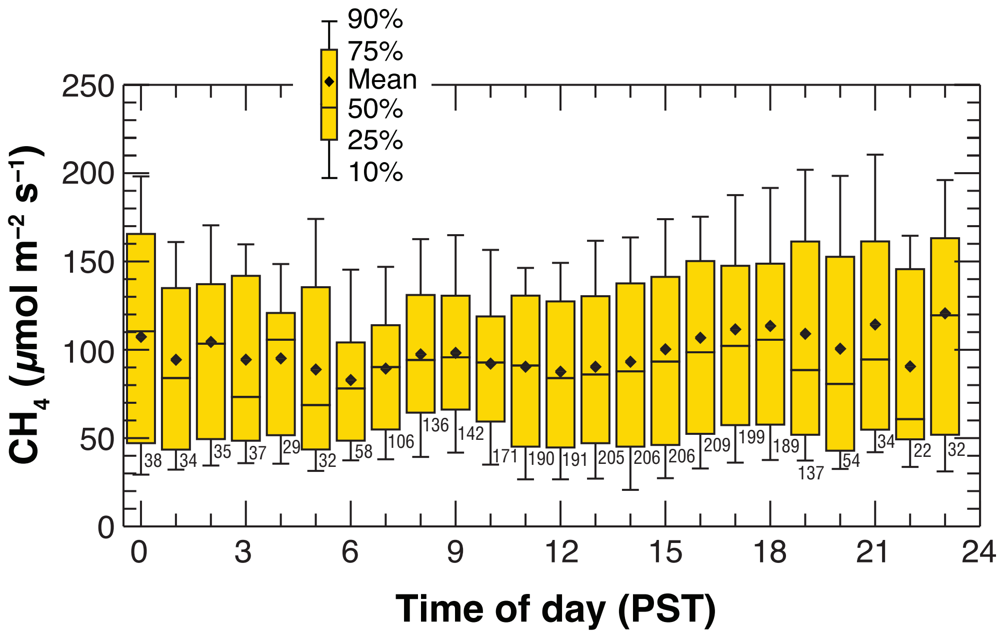

Figure 6: (a) Diurnal course of filled CH_4 fluxes from the EC-2 system in the entire study period.

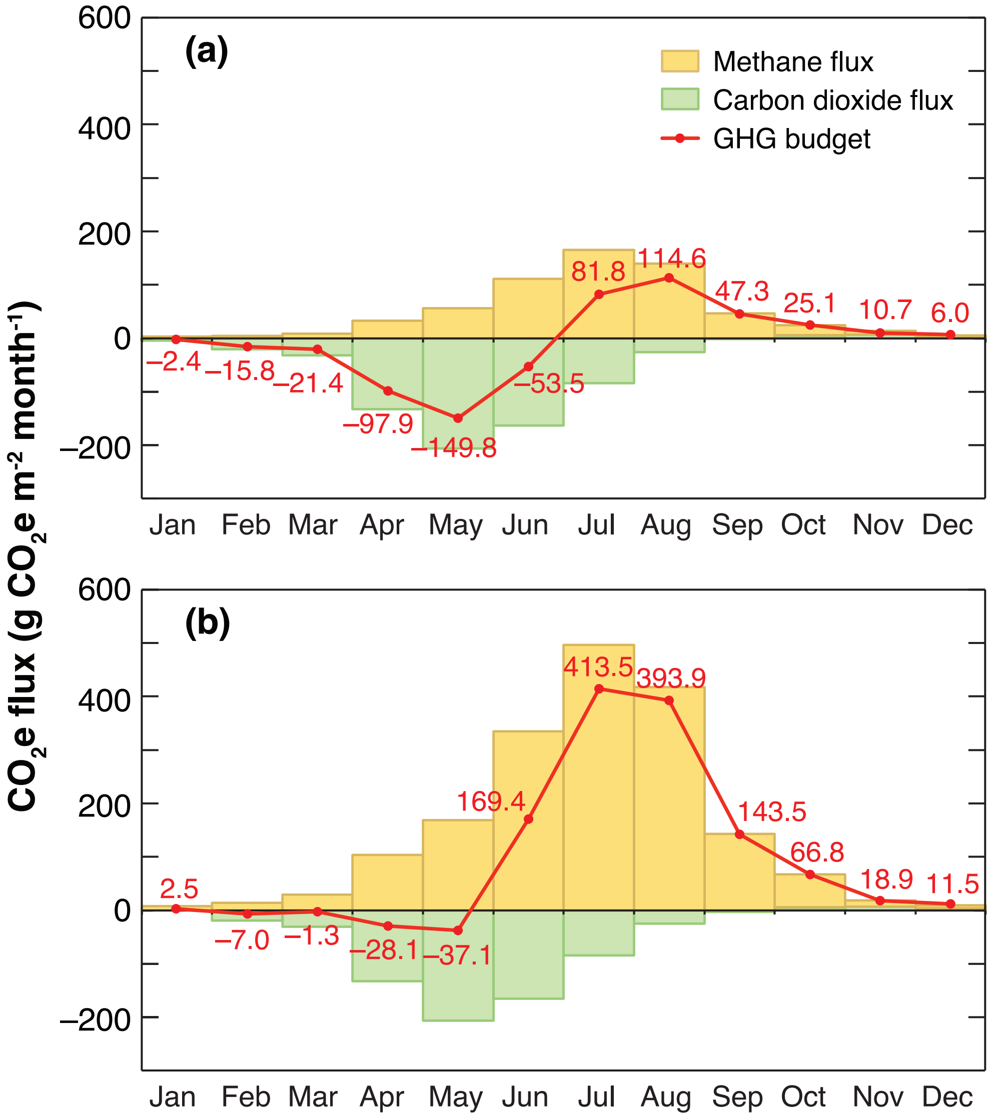

Figure 7: EC-measured monthly CO_2, CH_4 and net GHGs fluxes shown as CO_2e totals by using (a) 100-year and (b) 20-year GWPs. Missing data were gap-filled.

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565 Table 1: Monthly EC-measured and gap-filled NEE (CO_2 fluxes), CH_4 fluxes, CO_2e fluxes using 20-year GWP, and CO_2e fluxes using 100-year GWP at the study site during the study period.

Month	R_e (g CO_2-C m^{-2} month^{-1})	GEP	NEE	CH_4 fluxes (mg CH_4-C m^{-2} month^{-1})	20-year CO_2e fluxes (g CO_2e m^{-2} month^{-1})	100-year CO_2e fluxes (g CO_2e m^{-2} month^{-1})
Jan	6.17	7.50	-1.33	66	2.5	-2.4
Feb	6.94	12.46	-5.52	118	-7.0	-15.8
Mar	17.33	25.89	-8.59	269	-1.3	-21.4
Apr	23.52	59.73	-36.21	933	-28.0	-97.8
May	36.46	92.63	-56.20	1506	-37.0	-149.6
Jun	26.13	71.10	-44.97	2980	169.5	-53.3
Jul	38.53	61.47	-22.94	4436	413.6	81.8
Aug	36.15	42.97	-6.82	3734	393.9	114.6
Sep	24.84	25.08	-0.21	1286	143.5	47.3
Oct	10.76	9.58	1.18	557	66.8	25.2
Nov	5.16	3.39	1.77	111	18.9	10.6
Dec	3.63	2.79	0.87	74	11.5	6.0
Study year	g CO_2-C m^{-2} year^{-1}			g CH_4-C m^{-2} year^{-1}	g CO_2e m^{-2} year^{-1}	
	236	415	-179	16	1147	-55

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570 Table 2: Comparison of annual NEE, R_e and GEP, over different ecosystems (vegetation covers) in the Vancouver region using EC measurements. Sorted by magnitude of -NEE/GEP ratio.

Site	Land cover	NEE	R_e	GEP	-NEE/GEP
		g C m^{-2} year^{-1}			
Burns Bog (this study) Delta, BC	Rewetted raised bog ecosystem	-179	236	415	43%
Westham Island (CA-Wes)* Delta, BC	Unmanaged grassland	-222	1215	1438	15%
Campbell River (CA-Ca1)* Vancouver Island	Douglas-fir forest (~55 yrs)	-328^{+}	1830^{+}	2158^{+}	15%
Buckley Bay (CA-Ca3)* Vancouver Island	Douglas-fir forest (~15 yrs)	64^{+}	1487^{+}	1423^{+}	-4%

* Site identifier in global FLUXNET database (http://fluxnet.ornl.gov).
$^{+}$ Data from Krishnan et al., 2009 before fertilisation.

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