

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, agriculture, and other purposes, 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 (CO₂) sinks. However, rewetting may also cause substantial emissions of the more potent greenhouse gas (GHG) methane (CH₄). Our knowledge on the exchange of CO₂ and CH₄ following rewetting during restoration of disturbed peatlands is currently limited. This study quantifies annual fluxes of CO₂ and CH₄ 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 CO₂ and CH₄ 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 CO₂ budget of the rewetted area was -179 ± 26.2 g CO₂-C m⁻² year⁻¹ (CO₂ sink) and the annual CH₄ budget was 17 ± 1.0 g CH₄-C m⁻² year⁻¹ (CH₄ source). Gross ecosystem productivity (GEP) exceeded ecosystem respiration (*R_e*) during summer months (June-August), causing a net CO₂ uptake. In summer, high CH₄ emissions (121 mg CH₄-C m⁻² day⁻¹) were measured. In winter (December-February), while roughly equal magnitudes of GEP and *R_e* made the study area CO₂ neutral, very low CH₄ emissions (9 mg CH₄-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 suppressed *R_e*. With low temperatures in winter, CH₄ emission was more suppressed than *R_e*. Annual net GHG flux from CO₂ and CH₄ expressed in terms of CO₂ equivalents (CO₂e) during the study period totalled to -22 ± 103.1 g CO₂e m⁻² year⁻¹ (net CO₂e sink) and 1248 ± 147.6 g CO₂e m⁻² year⁻¹ (net CO₂e source) by using 100-year and

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20-year global warming potential values, respectively. Consequently, the ecosystem was almost CO₂e neutral during the study period expressed on a 100-year time horizon but was a significant CO₂e source on a 20-year time horizon.

40 1 Introduction

45 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; Mitsch et al., 2010) but 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 (Bridgman et al., 2006; Lal, 2008; Wisniewski and Sampson, 2012). On the other hand, they emit significant quantities of methane (CH₄), a powerful greenhouse gas (GHG), which is responsible for 30% of all global CH₄ emissions (Bergamaschi et al., 2007; Bloom et al., 2010; Ciais et al., 2013) due to anaerobic microbial decomposition (Aurela et al., 2001; Rinne et al., 2007). Peatlands are the most widespread of all wetland types in the world representing 50 to 70% of global wetlands (Roulet, 2000; Yu et al., 2010. Peatlands around the world sequester around 50 g CO₂-C m⁻² year⁻¹ (Roulet et al., 2007; Christensen et al., 2012; Humphreys et al., 2014; McVeigh et al., 2014; Peichl et al., 2014, Pelletier et al., 2015) and emit around 12 g CH₄-C m⁻² year⁻¹ (Abdalla et al., 2016; Brown et al., 2014; Jackowicz-Korczynski et al., 2010; Lai et al., 2014; Urbanova et al., 2013). Furthermore, it has been shown that it is crucial to include peatlands in the modelling and analysis of the global C cycle (Frolking et al., 2013; Kleinen et al., 2010; Wania et al., 2009).

55 Many peatlands have been harvested and continue to be disturbed by the extraction of peat for horticultural use and conversion to agriculture as well as other purposes. 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 CO₂ (Langeveld et al., 1997; Petrescu et al., 2015; Tapio-Biström et al., 2012). Additionally, degraded peat increases the risk of peatland fires, which could consequently cause significant CO₂ 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.

65 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 CO₂ and CH₄ fluxes. Raising the water level has been found to suppress the CO₂ efflux from the soil and result in an increase in net CO₂ uptake by native bog vegetation (Komulainen et al., 1999). CH₄ emissions from rewetted sections in a bog in Finland were three times higher than the release from the disturbed and dry

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area (Tuittila et al., 2000). Another study found similar rates of CH₄ 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 CO₂ emissions (Finér and Laine, 1998; Minkinen and Laine, 1998). In [other studies](#), re-establishing the conditions permitting peat formation also initially increased CH₄ 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, [year-round](#) 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 CO₂ and/or CH₄ 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 CO₂ and CH₄ 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 CO₂ and CH₄ 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 CO₂ and CH₄.

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 ([2,042 ha](#)) 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 CO₂ and CH₄ exchanges using primarily chamber systems in several plots representative of disturbed areas of the BBCEA, where some plots were rewetted and others were not. The study found substantial emissions of CH₄ primarily in recently rewetted plots, with highest emissions [associated with high water tables](#). 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 CO₂ and CH₄ exchanges using EC technique to provide spatially more representative fluxes at a recently rewetted plot.

The current study site is located in a harvested, disturbed, and rewetted area in the centre of the BBCEA (122°59'05.87"W, 49°07'47.20"N, WGS-84) with dimensions of 400 m by 250 m ([Fig. 1](#)). 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

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165 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). Based on the weather data for 1981 to 2010 from the closest
Environment Canada weather station, Vancouver International Airport, the average annual temperature was 10.4 °C and
average annual precipitation was 1062 mm. 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
 170 September. In September and October, a water table rise due to the increase in precipitation and reduced evapotranspiration
(ET) (Fig. 2) as a consequence of reduced available energy and senescence of sedges was observed, which is similar to water
table observations in other temperate wetlands (Lafleur et al., 2005; Rydin et al., 2013). 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
 175 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

180 3.1 Climate measurements

Weather variables were continuously measured in order to determine climatic controls of CO₂ and CH₄ 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
 185 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
 ($\frac{T_{s,5cm}}{\lambda_{s,5cm}}, \frac{T_{s,10cm}}{\lambda_{s,10cm}},$ and $\frac{T_{s,50cm}}{\lambda_{s,50cm}}$). A pressure transducer (CS400, CSI) was installed on July 28th 2015 in an observation well west of
 190 the tower to continuously measure WTH for the remainder of the study period. A soil volumetric water content (θ_{wv}) sensor
(CS616, CSI) was inserted vertically to measure integrated θ_{wv} from the surface to a depth of 0.30 m.

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195 **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 CO₂/H₂O infrared gas analyzer (IRGA, LI-7500, LI-COR Inc.). The path separation between CSAT-3 and LI-7500 was 5 cm. [The CSAT-3 measured the longitudinal, transverse and vertical components of the wind vector and sonic temperature and output data at 10 Hz.](#) The IRGA measured water vapor density (ρ_v) and CO₂ 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 CO₂ ([NEE](#)) were calculated in post-processing of 30-min data 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 CH₄ 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 H₂O/CO₂ IRGA (LI-7200, LI-COR Inc., 20 Hz) and an open-path gas analyzer to measure the partial density of CH₄ (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 CH₄ (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 the climate data \(<1% of the year\) were filled using measurements at nearby climate stations.](#) Small gaps (<60 minutes) of missing CO₂, H₂O, and CH₄ fluxes were filled by linear interpolation. [Longer gaps in H₂O fluxes were filled with the online tool developed by the Max Planck Institute for Biogeochemistry in Jena, Germany. This tool uses the look-up table method documented in Falge et al. \(2001\) and Reichstein et al. \(2005\).](#) Longer gaps were filled using empirical relationships between CO₂ or CH₄ fluxes and environmental variables. Two-year (from July 2014 to June 2016) of measurements of CO₂ 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 CO₂, 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, CO₂ fluxes, H , LE from EC-1 and CH₄ 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). [In this study, net fluxes of CO₂ and CH₄ toward the ecosystem surface are negative and net fluxes from the ecosystem surface to the atmosphere are positive. Therefore, negative NEE and \$F_m\$ represent net CO₂ and CH₄ uptake, respectively.](#)

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3.3.1 Gap filling of CO₂ flux data

For gaps longer than 2 hours in CO₂ fluxes, the CO₂ flux (e.g., net ecosystem exchange, NEE) was modelled as the difference between ecosystem respiration (R_e) and gross ecosystem productivity (GEP) i.e. $NEE = R_e - GEP$. 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):

$$R_e = \frac{1}{r_1 r_2 T_{s,5cm} + r_3} \quad (1)$$

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. For each day of the year, the parameters r_1 , r_2 , and r_3 for R_e were determined independently using a moving ± 60 -day window centered on that day, 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 226 and 245 g C m⁻² year⁻¹.

GEP was first partitioned from measured daytime NEE using modelled R_e . Any missing GEP data were then modelled using the photosynthetic light-response curves (Ögren and Evans, 1993) based on photosynthetic photon flux density (PPFD in $\mu\text{mol m}^{-2} \text{s}^{-1}$):

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

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). For each day of the year, the time-varying parameters MQY and P_M were determined independently using a moving ± 45 -day window centered on that day, 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.

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3.3.2 Gap filling of CH₄ flux data

CH₄ fluxes with quality flags 0 and 1 according to Mauder and Foken (2004) were plotted against all relevant variables including NEE, WTH, θ_w , T_a , $T_{s,5cm}$, $T_{s,10cm}$, and $T_{s,50cm}$. The highest correlation between a single variable and the CH₄ flux was found for soil temperature using an exponential relationship (Fig. S3). Of the soil temperatures measured at three different depths, $T_{s,10cm}$ explained the highest proportion of the variance in CH₄ flux (Table S1). Therefore, $T_{s,10cm}$ was used to build an initial model and a logarithmic transformation of the CH₄ fluxes was applied to remove the heteroscedasticity and permit the use of a linear regression model. Then the residual analysis was applied to explore whether the variance in the residual could be explained by other controls. The residual was defined as the ratio of the measured CH₄ fluxes to the modelled CH₄ fluxes from the initial model. Based on the residual analysis, the main contributor to the residual, WTH, explained 7% of the variance (Table S2). Additionally, there was a hysteresis relationship between CH₄ flux and WTH (Fig. S4). In order to have a more robust gap filling model, $T_{s,10cm}$ and WTH were used to fill the gaps in CH₄ fluxes. We used a combination of an exponential temperature response function and a linear WTH function as follows:

$$F_{CH_4} = (aWTH + b)e^{cT_{s,10cm}} \quad (3)$$

where a , b , and c are time-varying empirical parameters. The three parameters were fitted separately for each day, using a moving window of ± 105 days using all data from the study period when friction velocity was greater than 0.08 m s^{-1} . Overall, 76% of the variance of the CH₄ fluxes was explained by $T_{s,10cm}$ and WTH. The combination of soil temperature and WTH has also been shown to explain a large proportion of the observed variances in CH₄ fluxes in peatlands in other studies (Brown et al., 2014; Goodrich et al., 2015).

3.3.3 Error estimates

The uncertainty associated with annual estimates of NEE, GEP, R_e and CH₄ fluxes resulting from gap filling and due to different window sizes was quantified as follows: First, in the annual dataset of half-hourly fluxes random gaps were inserted using Monte Carlo simulation (Griffis et al., 2003; Krishnan et al., 2006; Paul-Limoges et al., 2015); The maximum number of gaps were set to 40 and the maximum length was set to 10 days resulting in total gaps of on average 28% of the year (and up to 40% of the year). The Monte Carlo simulation was run 500 times and the 95% confidence intervals were used to calculate the uncertainty of the annual sums.

Secondly, the uncertainty associated with choosing different window sizes for the derivation of the relationships in the gap-filling (see Section 3.3.1 and 3.3.2) was estimated from a range of annual values obtained using window sizes of 30, 45, 60, 75, 90, 120, 150, 180, and 365 days for GEP, R_e , and NEE; the same selections of window sizes with three additions (210, 240, and 270 days) were applied for calculating the uncertainty of the annual CH₄ budget. The overall uncertainty in the

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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 $T_{s,10cm}$, it was

used to build a model to fill the gaps in CH₄ fluxes.

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annual estimates of NEE, GEP, R_c and CH_4 fluxes was then obtained by taking the square root of the sum of squares of the error from the gap filling (Monte Carlo simulation) and the uncertainty of the estimates due to different window sizes.

325 3.4 Calculating CO₂e

The combined effect all long-lived greenhouse gases was compared for CO₂ and CH₄ by converting the molar fluxes of CO₂ and CH₄ into time-integrated radiative forcing (e.g. global warming potential, GWP) expressed on a mass basis in terms of CO₂ equivalents (g CO₂e m⁻² s⁻¹) as follows:

$$330 \quad CO_2e \text{ (g)} = m_{CO_2} F_c + GWP_{CH_4} m_{CH_4} F_m \quad (4)$$

GWP_{CH_4} is the mass-based GWP for the CH₄ (g g⁻¹), m_{CO_2} is the molecular mass of CO₂ (44.01 g mol⁻¹), and m_{CH_4} is the molecular mass of CH₄ (16.04 g mol⁻¹). In this study, a 100-year GWP of CH₄ of 28, and 20-year GWP of CH₄ of 84, were used respectively (IPCC, 2014). N₂O fluxes have been neglected in this study because previous chamber-based measurements during the growing season found no significant emissions or uptake of N₂O in all study plots in the BBCEA (Christen et al., 2016).

4 Results and Discussion

4.1 Weather

340 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 °C. Mean monthly T_a ranged between 4.4 (Jan 2016) and 19.3 °C (Jul 2015). The study site received a total annual precipitation of 1062 mm, of which 16% (174 mm) fell during the warm half year (Apr-Sep) and 84% (888 mm) during the cold half year (Oct-Mar) (Fig. 2). 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.

345 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

350 Cumulative turbulent source areas were calculated using the analytical turbulent source area (turbulent footprint) model (Kormann and Meixner, 2001) following the procedure outlined in Christen et al. (2011). The 80% contour line (enclosing

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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).

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4.2.2 Vegetation cover and water table changes

Mosses and white beak sedge (the common name of *Rhynchospora alba*) 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 CO₂ exchange

4.3.1 Annual, seasonal and monthly NEE, R_e and GEP

Overall, the study area was a CO₂ 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 CO₂ 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 CO₂-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 CO₂ except in October, November and December (Fig. 3, Table 1). Monthly net fluxes of CO₂ (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).

Compared to a large seasonal amplitude in monthly GEP, R_e showed less variability over the year. The highest rate of increase in the magnitude of NEE and the highest magnitude of NEE both occurred early in growing season (Fig. 3). 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 CO₂ sequestration (-NEE is 43 % of GEP, as opposed to 15% for the unmanaged grassland site and mature forest).

The annual NEE in this study was more negative than in the majority of previously reported NEE values for undisturbed temperate peatlands, which were weak sinks, typically in the range of $-50 \text{ g C m}^{-2} \text{ year}^{-1}$ (Christensen et al., 2012; Humphreys et al., 2014; Matthias et al., 2014; McVeigh et al., 2014; Pelletier et al., 2015; Roulet et al., 2007). Values that are comparable to the current restored wetland were reported in five pristine temperate wetlands: $-248 \text{ g C m}^{-2} \text{ year}^{-1}$ (Lafleur et al., 2001), $-234 \text{ g C m}^{-2} \text{ year}^{-1}$ (Campbell et al., 2014), $-210 \text{ g C m}^{-2} \text{ year}^{-1}$ (Fortuniak et al., 2017), $-189 \text{ g C m}^{-2} \text{ year}^{-1}$ (Flanagan and Syed, 2011), and $-103 \text{ g C m}^{-2} \text{ year}^{-1}$ (Lund et al., 2010). The few datasets in the literature for NEE of restored wetlands showed a wide range of values. Some were CO₂ sources, with NEE ranging from $+103 \text{ g C m}^{-2} \text{ year}^{-1}$ to $+142 \text{ g C m}^{-2} \text{ year}^{-1}$ (Järveoja et al., 2016; Richards and Craft, 2015; Strack and Zuback, 2013). Other measurements in restored wetlands, however, were sinks, all of them stronger than in this study, with NEE values ranging from $-804 \text{ g C m}^{-2} \text{ year}^{-1}$ to $-270 \text{ g C m}^{-2} \text{ year}^{-1}$ (Anderson et al., 2016; Badiou et al., 2011; Hendriks et al., 2007; Herbst et al., 2013; Knox et al., 2015). In this study, values of R_e and GEP were lower than those found for a restored wetland at a comparable latitude in the central Netherlands with slightly lower annual temperature and precipitation (Hendriks et al., 2007). R_e and GEP in this study area were also lower than values for most pristine peatlands at comparable latitudes (Helfter et al., 2015; Levy and Gray, 2015). Comparably low R_e and GEP were reported from the 'Mer Bleue' boreal raised bog (Lafleur et al., 2001; Moore, 2002), and from an Atlantic blanket bog (McVeigh et al., 2014; Sottocornola and Kiely, 2010), both of which experienced a lower mean annual temperature.

It is important to estimate dissolved organic carbon (DOC) to determine a more complete ecosystem C budget. DOC lost from restored and pristine peatlands have been found typically to range from 3.4 to $16.1 \text{ g C m}^{-2} \text{ year}^{-1}$ (Hendriks et al., 2007; Koehler et al., 2011; Roulet et al., 2007; Waddington et al., 2010), although, Chu et al. (2014) reported a net DOC import for a marsh of $23 \pm 13 \text{ g C m}^{-2} \text{ year}^{-1}$. Estimation of DOC fluxes was based on regular (approx. monthly) water samples collected at 5 locations within the flux tower footprint using the headspace equilibration technique. Lateral flow was estimated as the residual of the water balance. D'Acunha et al. (2016) estimated DOC export for the current study area for Jan – Dec 2016 to be $22.4 \text{ g C m}^{-2} \text{ year}^{-1}$ (15% of annual NEE).

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4.3.2 Diurnal variability in CO₂ fluxes

The seasonally-changing diurnal course of gap-filled NEE with isopleths over time of day and year is shown in Fig. 4. The daily maximum in GEP changed with season resulting in the high magnitude of NEE during midday between May and July (~ -3.5 $\mu\text{mol m}^{-2} \text{s}^{-1}$) with the highest magnitude of NEE occurring in May. Nighttime NEE, i.e., R_e , showed relatively small variation with season, and on average was $<1 \mu\text{mol m}^{-2} \text{s}^{-1}$ for most of the study period. The rapid decrease in monthly R_e from May to June (Table 1) was caused by low R_e in early morning or at nightfall in June.

4.3.3 Ecosystem respiration

Figure 5 shows the relationship between nighttime R_e and $T_{s,scm}$ using the data for the entire study period. R_e increased with increasing $T_{s,scm}$ 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. S5). R_e showed different curves depending on season. In winter, R_e varied little with $T_{s,scm}$ and was close to zero. From February to May, the relationship became closer to logistic. In June and July, due to general warm condition ($>15^\circ\text{C}$), R_e remained nearly constant at $\sim 1 \mu\text{mol m}^{-2} \text{s}^{-1}$ (the fitted curve stayed in the plateau phase). 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 $T_{s,scm}$. 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 $T_{s,scm}$ were up to $0.4 \mu\text{mol m}^{-2} \text{s}^{-1}$.

Two other controls on R_e explored were air temperature (T_a) and WTH. The role of WTH was described above and T_a had a similar impact on R_e as $T_{s,scm}$ when $T_a < 16^\circ\text{C}$, 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 (Rocheffort et al., 2002; Weltzin et al., 2000). When the water table was below surface, R_e increased to near $1 \mu\text{mol m}^{-2} \text{s}^{-1}$ 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 $0.6 \mu\text{mol m}^{-2} \text{s}^{-1}$ when θ_w increased from 84% to 88%. Other than this range, θ_w had no more impact on R_e .

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刪除: 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 ($-3.5 \mu\text{mol m}^{-2} \text{s}^{-1}$). During nighttime, R_e was less varying with season, and on average was $\leq 1 \mu\text{mol m}^{-2} \text{s}^{-1}$ for most of the study period.

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4.3.4 Gross ecosystem productivity

475 Figure 6 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. S6). GEP reached a maximum in May with $92.63 \text{ g C m}^{-2} \text{ month}^{-1}$, and a minimum of 2.79 g C
 $\text{m}^{-2} \text{ month}^{-1}$ in December (Fig. 3, Table 1). GEP at light saturation reached roughly $5.09 \mu\text{mol m}^{-2} \text{ s}^{-1}$ in summer, and
480 remained below $2.49 \mu\text{mol m}^{-2} \text{ s}^{-1}$ 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 WTH and T_a . We found that WTH was not a control on GEP ($R^2 = 0.08$)
in the current study as the study area remained fairly wet throughout the year. Furthermore, the effect of T_a on GEP was less
and limited to a smaller temperature range, compared to T_a .

485 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 $\text{CH}_4\text{-C}$ budget was $17 \pm 1.0 \text{ g}$
 $\text{CH}_4\text{-C m}^{-2} \text{ yr}^{-1}$. CH_4 emissions were close to zero in winter ($5.2 \text{ mg CH}_4\text{-C m}^{-2} \text{ day}^{-1}$). Seasonally, it was a weaker CH_4
source in fall ($31.3 \text{ mg CH}_4\text{-C m}^{-2} \text{ day}^{-1}$) and spring ($36.4 \text{ mg CH}_4\text{-C m}^{-2} \text{ day}^{-1}$), and then became a much larger source in
490 summer ($126.0 \text{ mg CH}_4\text{-C m}^{-2} \text{ day}^{-1}$). Monthly emissions of CH_4 ranged from 93 (January) to 4371 (July) $\text{mg CH}_4\text{-C m}^{-2}$
 month^{-1} . 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 1.4 to 2.7 $\text{g CH}_4\text{-C m}^{-2} \text{ month}^{-1}$ in June
(Table 1). CH_4 emissions reached the peak in July ($4.4 \text{ g CH}_4\text{-C m}^{-2} \text{ month}^{-1}$) and held similar magnitude ($3.8 \text{ g CH}_4\text{-C m}^{-2}$
495 month^{-1}) in August even though the T_a had dropped. Although it has been suggested that in some peatlands, WTH acts as a
main control on CH_4 fluxes (Drösler et al., 2008; Knorr et al., 2009; Romanowicz et al., 1995; Roulet et al., 1993; Windsor
et al., 1992), it has also been found that CH_4 emissions from wet soils (where the water table fluctuates within a small range
near the surface) are highly dependent on T_a because the oxidation in a shallow top soil is negligible (Jackowicz-Korczynski
et al., 2010; Long et al., 2010; Olson et al., 2013; Rinne et al., 2007; Song et al., 2009). In our study, CH_4 emissions in the
summer months were relative high even when the water table dropped to around 20 cm below the surface, likely because the
500 peat maintained anaerobic conditions above the water table (as discussed in Hendriks et al., 2007). In addition, one needs to
consider the transport pathways for CH_4 which may help explain the higher CH_4 fluxes in summer. First, the presence of
sedges created an effective additional diffusion pathway for CH_4 through the plants' aerenchyma (Herbst et al., 2011; Treat
et al., 2007). Second, a high water table especially when it rises above the soil surface increases the diffusion resistance to
 CH_4 transport (Brown et al., 2014; Walter and Heimann, 2000). An additional reason for the lowest CH_4 emissions occurring

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540 in winter months could be the suppression from rain events (Goodrich et al., 2015) as 84% of rain fell at the site during the cold half-year.

545 The annual CH₄ flux in this study area was lower than CH₄ fluxes reported for other restored wetlands (Anderson et al., 2016; Hendriks et al., 2007; Knox et al., 2015; Mitsch et al., 2010). Despite the study area being flooded for most of the study year, CH₄ emissions were closer to fluxes measured over drained peatlands (Kroon et al., 2010; Schrier-Uijl et al., 2010). Only Herbst et al. (2013) reported an annual CH₄ flux from a restored wetland in Denmark that was lower than in this study (9 to 13 g CH₄-C m⁻² year⁻¹). Our annual CH₄ flux at 17 ± 1.0 g CH₄-C m⁻² year⁻¹ was comparable to an average natural temperate wetland CH₄ flux, which is typically around 15 g CH₄-C m⁻² year⁻¹ (Abdalla et al., 2016; Fortuniak et al., 2017; Nicolini et al., 2013; Turetsky et al., 2014). The CH₄ fluxes from a number of temperate and tropical pristine wetlands exceeded the CH₄ fluxes reported in this study, including emissions from marshes in the Southwestern US (130 g CH₄-C m⁻² year⁻¹, Whiting & Chanton, 2001), tropical wetlands in Costa Rica (82 g CH₄-C m⁻² year⁻¹, Nahlik & Mitsch, 2010), and marshes in the Midwestern US (50 g CH₄-C m⁻² year⁻¹, Koh et al., 2009). However, all these studies were conducted using chambers and the sampling frequency was at most once per month.

4.4.2 Diurnal variability in CH₄ fluxes

555 The ensemble diurnal courses of the CH₄ fluxes measured by the EC-2 system are shown in Fig. 7 from 16th June 2015 to 15th June 2016. Surprisingly, there was only a small diurnal variation observed for CH₄ fluxes in the summer months, while larger diurnal variations have been found in other studies (Juutinen et al., 2004; Long et al., 2010; Sun et al., 2013; Wang and Han, 2005). In the current study area, with changes in WTH and vegetation growth occurring during the year, there were likely several processes affecting CH₄ transport, which masked the diurnal pattern of CH₄ fluxes. Furthermore, *T_{s,5cm}* appeared to be the main environmental control on CH₄ fluxes in this study but did not have as strong effect on CH₄ emissions as found in previous studies. Thus CH₄ was continuously emitted at a similar rate during daytime and nighttime.

560 From January to March and October to December, the winter half-year, the study site had constant CH₄ emissions of less than 50 nmol m⁻² s⁻¹, and almost no diurnal variation was observed. July had the greatest CH₄ 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 of soil temperature and may be partly due to convective turbulent mixing caused by cooling during the evening (Godwin et al., 2013).

565 4.5 CO₂e exchange

Figure 8a and 8b show CO₂ and CH₄ fluxes expressed in terms of CO₂e using 100-year and 20-year GWPs, respectively. Considering fluxes of both GHGs together, this rewetted area was annually near to CO₂e neutral at 100-year scale with a net uptake by CO₂ (-656 g CO₂e m⁻² year⁻¹) nearly the same as CH₄ emissions (634 g CO₂e m⁻² year⁻¹). On shorter time horizon of 20 years, the study area represented a significant net climatic forcing in CO₂e terms as the net uptake of CO₂ (-656 g CO₂e m⁻² year⁻¹) was one-third that of CH₄ emissions (1904 g CO₂e m⁻² year⁻¹). In late spring and early summer, the early onset of

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刪除: Surprisingly, there was not much of a diurnal course observed for CH₄ fluxes. CH₄ was continuously emitted through day and night. Thermal effects such as recently reported by Poindexter et al., 2016 were not found. From January to March and October to December, the study site had constant CH₄ emissions of less than 50 nmol m⁻² s⁻¹, and almost no diurnal variation was observed. July had the greatest CH₄ 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.

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CO₂ sequestration in May and the time lag in CH₄ fluxes combined to represent a negative net GHG forcing, no matter which GWP time horizon was considered. The quick drop in CO₂ 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, CO₂ and CH₄ fluxes in terms of CO₂e, 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; a short-term campaign can be a good way to identify important site processes but the determination of the annual budget requires reliable long-term measurements.

Using GWP to classify a study area as a net GHG source or sink is useful; however, the appropriateness of this method in computing the actual radiative forcing has been questioned (e.g. sustained step-change in CO₂ and CH₄ fluxes can not be evaluated) and alternative models were proposed (Frolking and Roulet, 2007; Fuglested et al., 2000; Neubauer and Magonigal, 2015; Petrescu et al., 2015; Smith and Wigley, 2000).

5 Conclusions

The study area, a rewetted plot in the BBCEA undergoing ecological restoration, was a net CO₂ sink over the study period (-179 g ± 26.2 CO₂-C m⁻² year⁻¹). The study area was not a highly productive ecosystem (annual GEP = 415 ± 28.8 g CO₂-C m⁻² year⁻¹) but exhibited low R_e (annual R_e = 236 ± 16.4 g CO₂-C m⁻² year⁻¹), likely due to oxygen limitations. The annual CO₂ 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 CO₂ than the few other restored wetlands reported in the literature (Anderson et al., 2016; Jarveoja et al., 2016; Knox et al., 2015; Richards and Craft, 2015; Strack and Zuback, 2013). The major controls on CO₂ 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 CH₄ emissions were 17 ± 1.0 g CH₄-C m⁻² year⁻¹, which is lower than those reported for other restored wetlands (Anderson et al., 2016; Knox et al., 2015). CH₄ 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 CH₄ fluxes at the study area were not clearly apparent. T_{s,5cm} and WTH explained CH₄ fluxes best (R² = 0.76).

In terms of the C balance (DOC fluxes excluded), our results suggest that our study area in BBCEA was a net C sink (-163 ± 26.2 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 CO₂ and CH₄ fluxes expressed by GWPs, our results show that the ecosystem was almost CO₂e neutral (-22 ± 103.1 g CO₂e m⁻² year⁻¹) over a 100-year time

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655 horizon during the study period after a 7-year restoration. However, the rewetted area was a substantial net CO₂e source
| ($1248 \pm 147.6 \text{ g CO}_2\text{e m}^{-2} \text{ year}^{-1}$) on a 20-year time horizon due to the stronger GWP of CH₄ on shorter timescales.

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BC).

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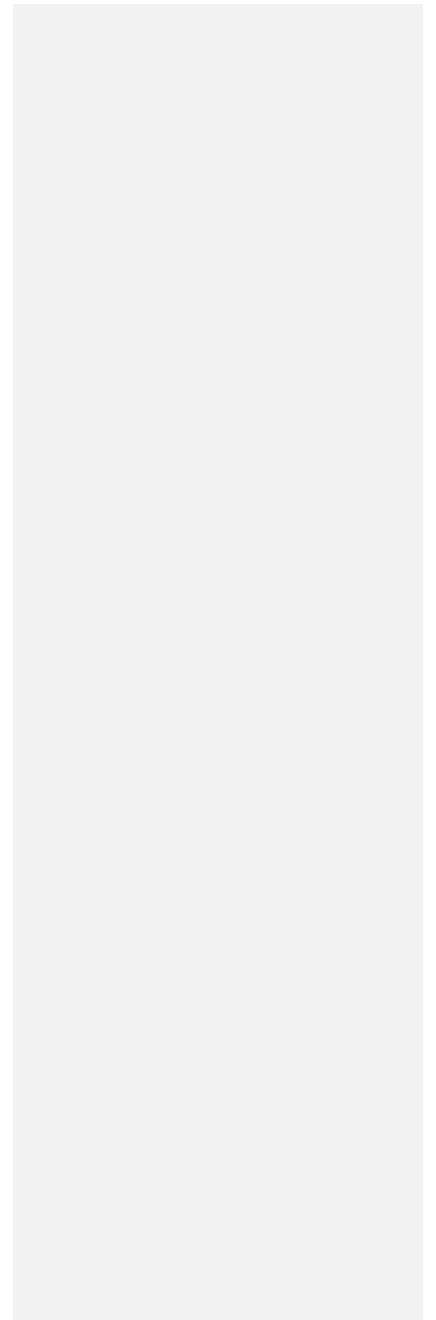
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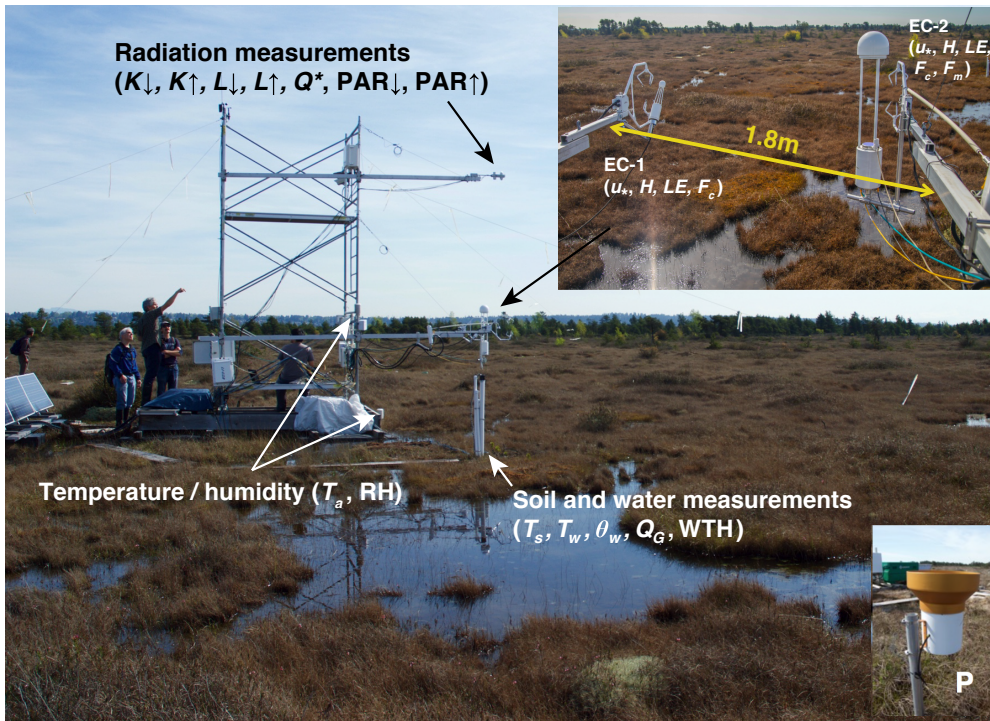
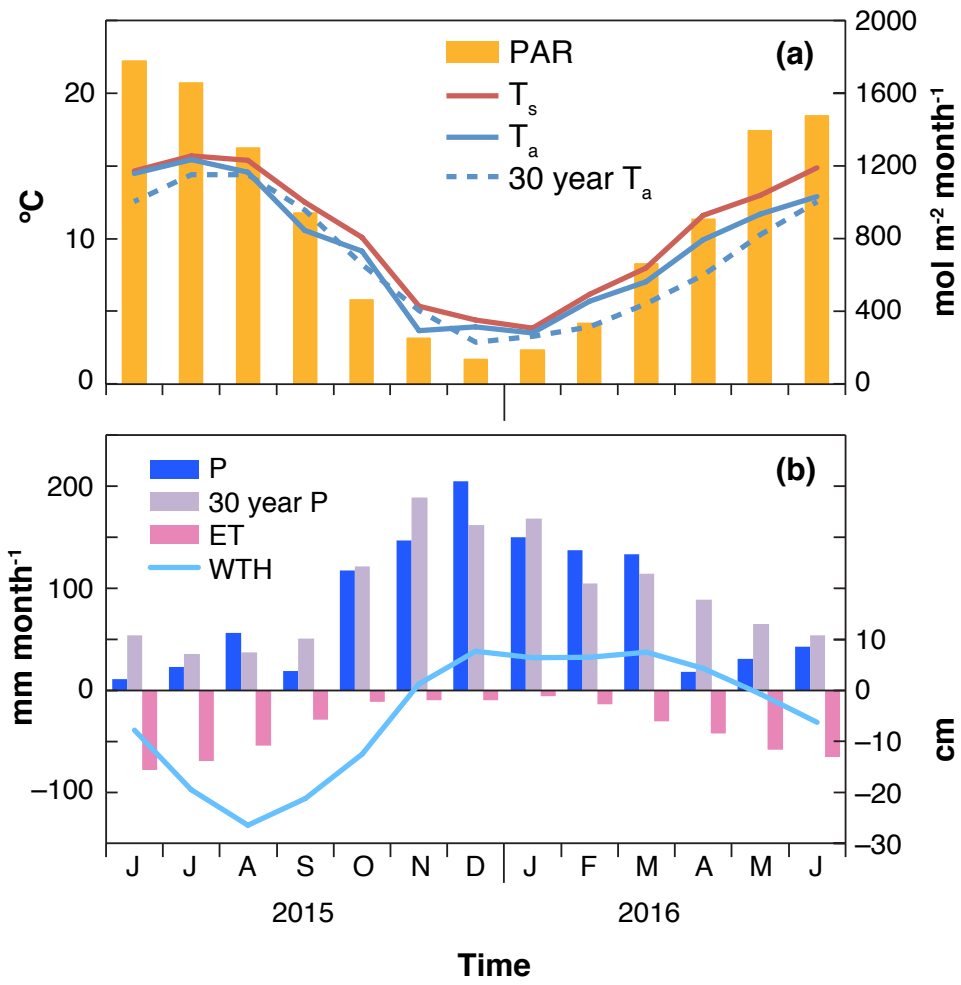


Figure 1: Flux tower on floating platform with EC-1 and EC-2 systems facing south and instruments that measured climate variables indicated (friction velocity (u_*), sensible heat flux (H), latent heat flux (LE), CO₂ flux (NEE), CH₄ flux (F_m), incoming shortwave radiation ($K \downarrow$), outgoing shortwave radiation ($K \uparrow$), incoming longwave radiation ($L \downarrow$), outgoing longwave radiation ($L \uparrow$), net all-wave radiation (Q^*), incoming PAR ($PAR \downarrow$), outgoing PAR ($PAR \uparrow$), 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 height (WTH), and precipitation (P)).

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925 [Figure 2: The annual course of weather variables \(\$T_s\$, \$T_a\$, P, and PAR\), ET, and WTH. The 30-year climate normals \(30-year \$T_a\$ and P\) were measured at Vancouver International Airport \(Data: Environment Canada\).](#)

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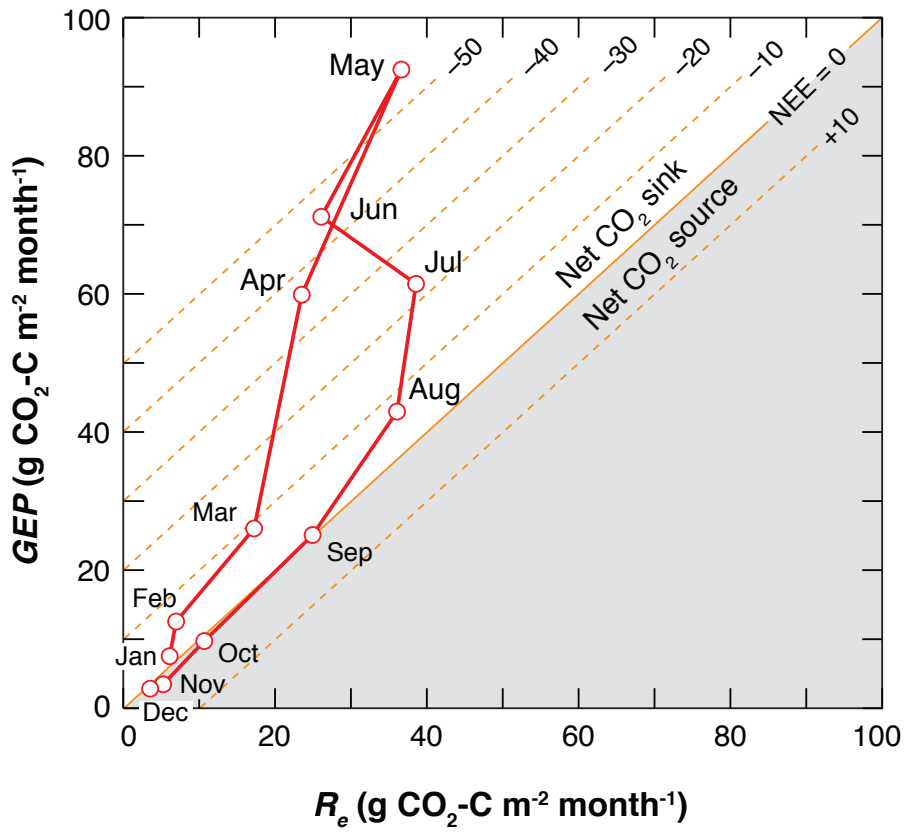


Figure 3: Monthly gap-filled R_e (x-axis) drawn against GEP (y-axis). The resulting NEE can be read off the diagonal lines. The thick 1:1 line shows carbon neutrality, while lines in the upper right are of increasingly negative NEE (uptake) and lines towards the lower right are positive NEE (net source).

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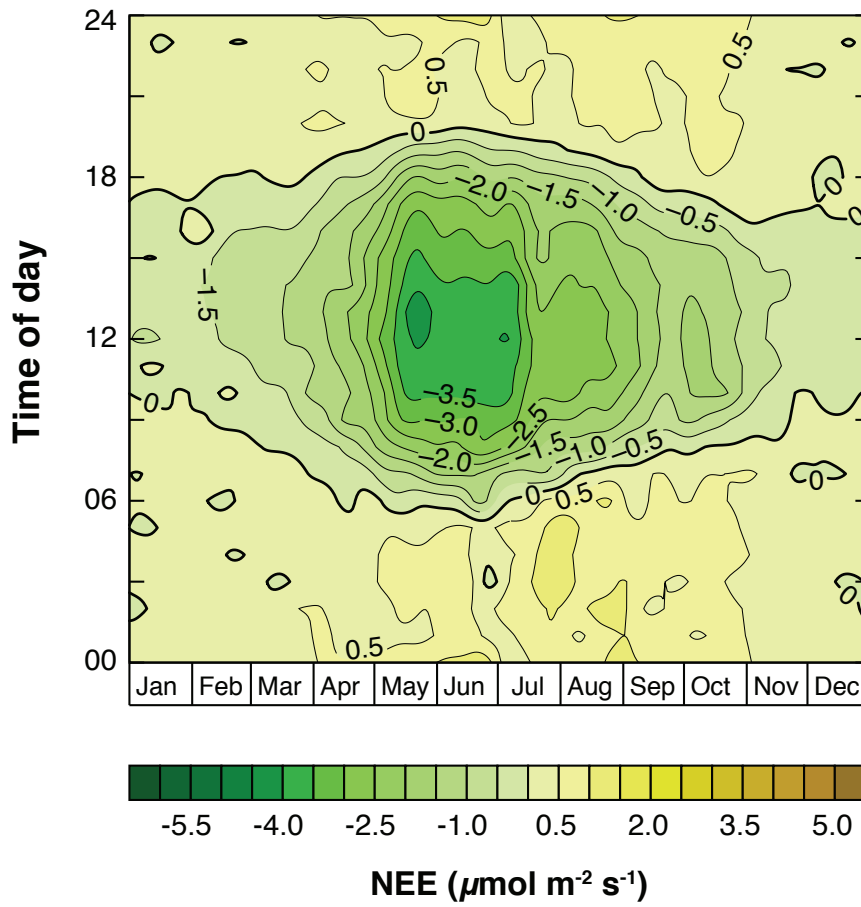
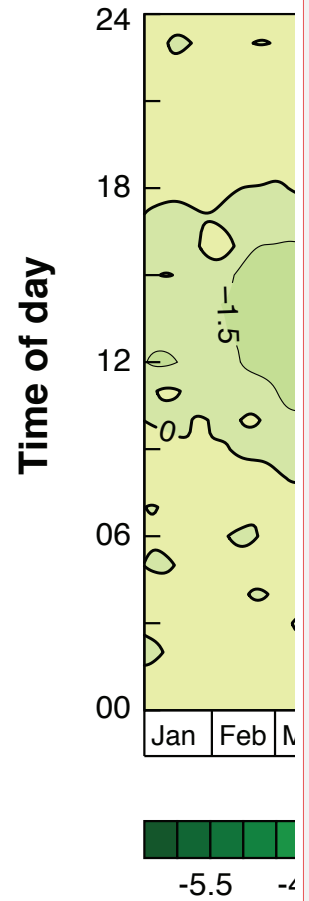
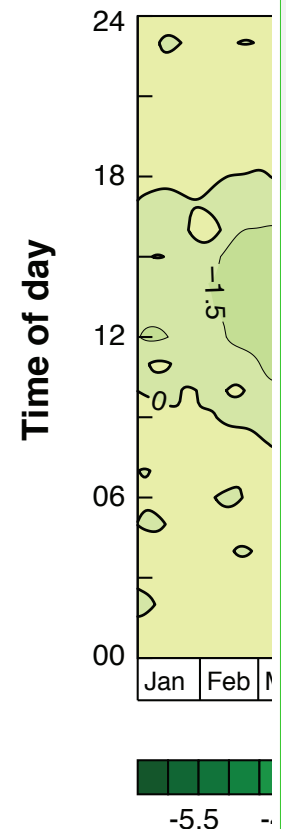
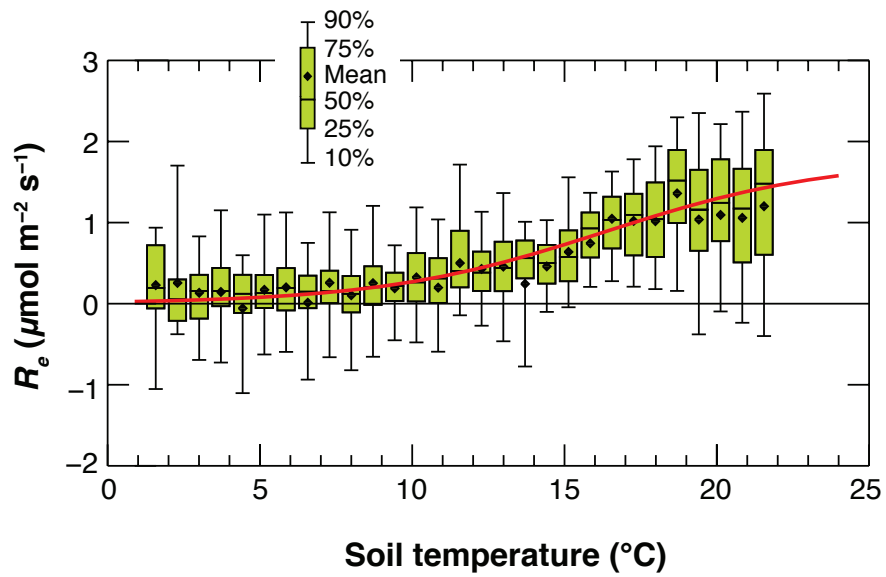


Figure 4: Isopleths of gap-filled NEE (net CO₂ fluxes) from the EC-1 system plotted as a composite in the study year. The graph uses a Gaussian filter of $\sigma = 45$ days (which conserves total NEE) to graphically smooth horizontal variations.



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940 Figure 5: 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. S5 in supplement for seasonal differences. Negative R_e values were caused by measurement uncertainties.

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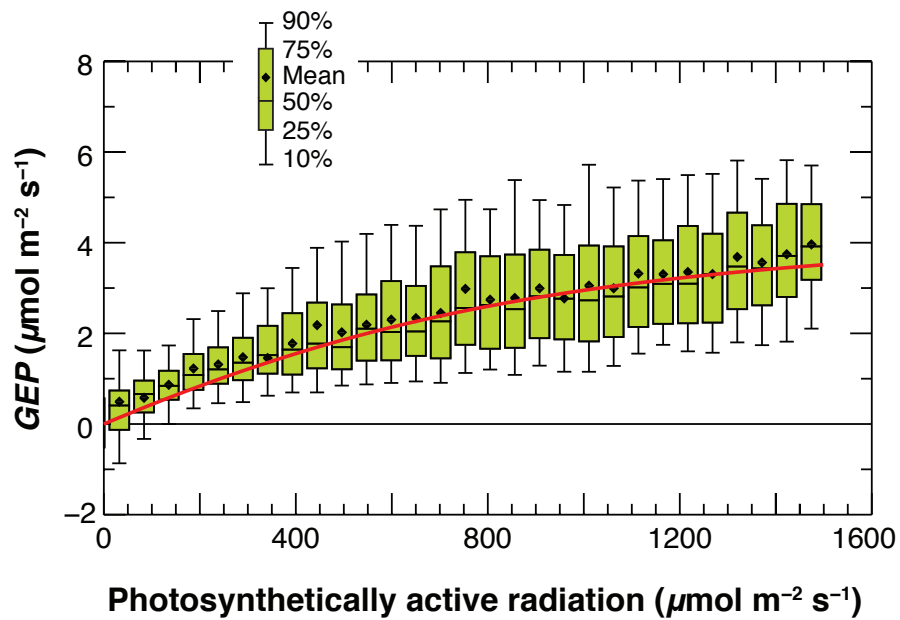


Figure 6: Annual light response curve determined from the daytime 30-minute NEE measurements and Eq. 1, i.e., $GEP = R_e + \text{-NEE}$. The curves are the best fit of the Eq. 2. PPFD was binned for 30 classes from 0 to $1500 \mu\text{mol m}^{-2} \text{s}^{-1}$. Annual MQY was $4.00 \text{ mmol C mol}^{-1} \text{ photons}$, P_M was $4.68 \text{ umol m}^{-2} \text{ s}^{-1}$, and C_v was 0.7 (fixed).

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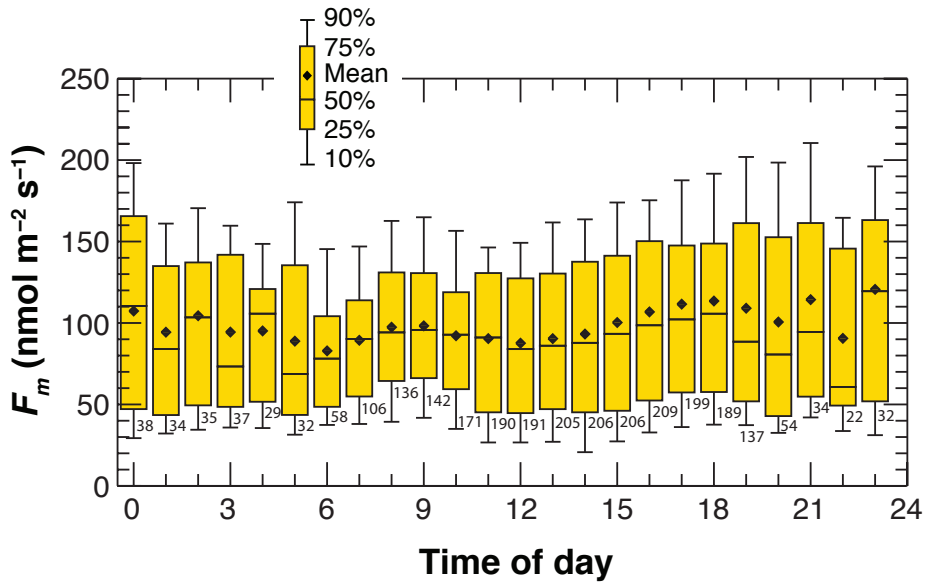
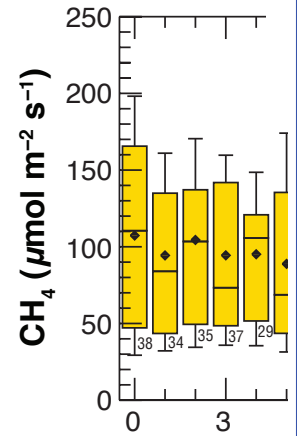


Figure 7: The ensemble diurnal course of measured CH₄ fluxes from the EC-2 system during the study period. More datasets were available from the summer half-year than from the winter half-year.

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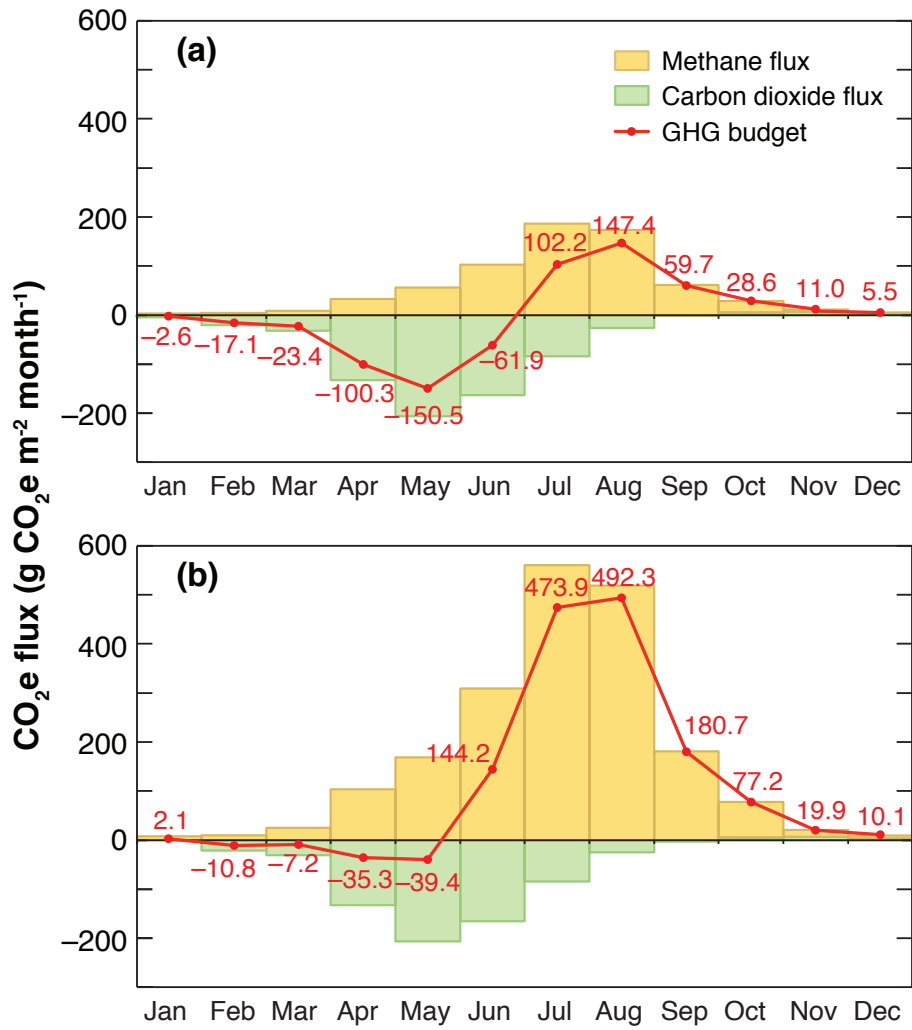
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刪除: Diurnal course of filled CH₄ fluxes from the EC-2 system in the entire study period.

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960 Figure 8: EC-measured monthly CO₂, CH₄ and net GHGs fluxes shown as CO₂e totals by using (a) 100-year and (b) 20-year GWPs. Missing data were gap-filled.

Table 1: Monthly EC-measured and gap-filled NEE (CO₂ fluxes), CH₄ fluxes, CO₂e fluxes using 20-year GWP, and CO₂e fluxes using 100-year GWP at the study site during the study period.

Month	<i>R_e</i>	GEP	NEE	CH ₄ fluxes	20-year CO ₂ e fluxes	100-year CO ₂ e fluxes
	(g CO ₂ -C m ⁻² month ⁻¹)			(mg CH ₄ -C m ⁻² month ⁻¹)	(g CO ₂ e m ⁻² month ⁻¹)	(g CO ₂ e m ⁻² month ⁻¹)
Jan	6.17	7.50	-1.33	93	2.06	-2.57
Feb	6.94	12.46	-5.52	224	-10.82	-17.09
Mar	17.33	25.89	-8.59	465	-7.18	-23.38
Apr	23.52	59.73	-36.21	1170	-35.33	-100.29
May	36.46	92.63	-56.20	1643	-39.42	-150.53
Jun	26.13	71.10	-44.97	2670	144.23	-61.85
Jul	38.53	61.47	-22.94	4371	474.88	102.22
Aug	36.15	42.97	-6.82	3813	492.32	147.44
Sep	24.84	25.08	-0.21	1650	180.67	59.71
Oct	10.76	9.58	1.18	930	77.23	28.62
Nov	5.16	3.39	1.77	240	19.93	10.97
Dec	3.63	2.79	0.87	155	10.13	5.50
Study year	g CO ₂ -C m ⁻² year ⁻¹			g CH ₄ -C m ⁻² year ⁻¹		g CO ₂ e m ⁻² year ⁻¹
	236 ± 16.4	415 ± 28.8	-179 ± 26.2	17 ± 1	1248 ± 147.6	22 ± 103.1

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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%

1050 * Site identifier in global FLUXNET database (<http://fluxnet.ornl.gov>).

⁺ Data from Krishnan et al., 2009 before fertilisation.

REFeree COMMENTS:

Referee #2

1055

MAIN COMMENTS TO THE AUTHOR(S)

1) There has been no attempt to discuss or quantify the likely size of uncertainties of the fluxes, especially as they relate to annual fluxes and CO₂-e values. It is not really acceptable to publish these data now without considering the likely size of uncertainties. Given my comments below about gap filling CH₄ fluxes, I strongly suggest that a due consideration of the magnitude of uncertainties at the annual timescale is warranted.

1060

[Response]

As suggested, we have estimated uncertainties and added a new section (Section 3.3.3) describing the method we used to estimate the uncertainties, followed by including related text in the Results and Discussion as follows:

1065

“3.3.3 Error estimates

The uncertainty associated with annual estimates of NEE, GEP, R_e and CH₄ fluxes resulting from gap filling and due to different window sizes was quantified as follows: First, in the annual dataset of half-hourly fluxes random gaps were inserted using Monte Carlo simulation (Griffis et al., 2003; Krishnan et al., 2006; Paul-Limoges et al., 2015); The maximum number of gaps were set to 40 and the maximum length was set to 10 days resulting in total gaps of on average 28% of the year (and up to 40% of the year). The Monte Carlo simulation was run 500 times and the 95% confidence intervals were used to calculate the uncertainty of the annual sums.

1070

Secondly, the uncertainty associated with choosing different window sizes for the derivation of the relationships in the gap-filling (see Section 3.3.1 and 3.3.2) was estimated from a range of annual values obtained using window sizes of 30, 45, 60, 75, 90, 120, 150, 180, and 365 days for GEP, R_e , and NEE; the same selections of window sizes with three additions (210, 240, and 270 days) were applied for calculating the uncertainty of the annual CH₄ budget. The overall uncertainty in the annual estimates of NEE, GEP, R_e and CH₄ fluxes was then obtained by taking the square root of the sum of squares of the error from the gap filling (Monte Carlo simulation) and the uncertainty of the estimates due to different window sizes.”

1075

The average and uncertainty values for annual NEE, R_e , GEP, and CH₄ budget were -179 ± 26.2 , 236 ± 16.4 , 415 ± 28.8 , and 17 ± 1.0 g C m⁻² year⁻¹, respectively. All numbers in the abstract and manuscript, including CO₂e estimates (1248 ± 147.6 gCO₂e m⁻² year⁻¹ for the 20-year time horizon and -22 ± 103.1 gCO₂e m⁻² year⁻¹ for the 100-year time horizon), have been updated accordingly.

1080

1085 2) My comments about gap filling CH₄ fluxes have not really been adequately addressed. I suggest that the nature of
the relationship settled on in 3.3.2 be supported by a figure, even if it is in supplementary material. I do find it
surprising that an r² as high as 66% was found, unless it is simply the result of the extremely wide range of flux
values. If that were the case, I'd be more concerned about r² within the region of the relationship where most of the
annual flux was derived (i.e. during warm temperatures). This is also why an estimate of uncertainty is required.
1090 Moreover, the authors hinted that little CH₄ flux data were available in winter, increasing uncertainty. They also hint
(lines 328-329) that there may well have been hysteresis in the temperature vs F_m relationship. It may well be more
defensible to gap fill using the means of daily 30-minute measurements to construct daily means. But without seeing
the data, it's difficult to judge. Suggest looking at Goodrich et al. (2015) JGR-BG (DOI: 10.1002/2014JG002844) for a
situation with strong hysteresis in methane fluxes from a wetland, where a "simple" regression-based approach was
1095 demonstrated to be inadequate.

[Response]

We have improved our analysis with the aim of determining the contributions of additional environmental controls (different
depths of soil temperature, air temperature, water table depth, soil water content, and NEE). We have described the
additional analyses in the text, and have added two figures and two tables to provide additional information.

1100

We have rewritten Section 3.3.2 as follows:

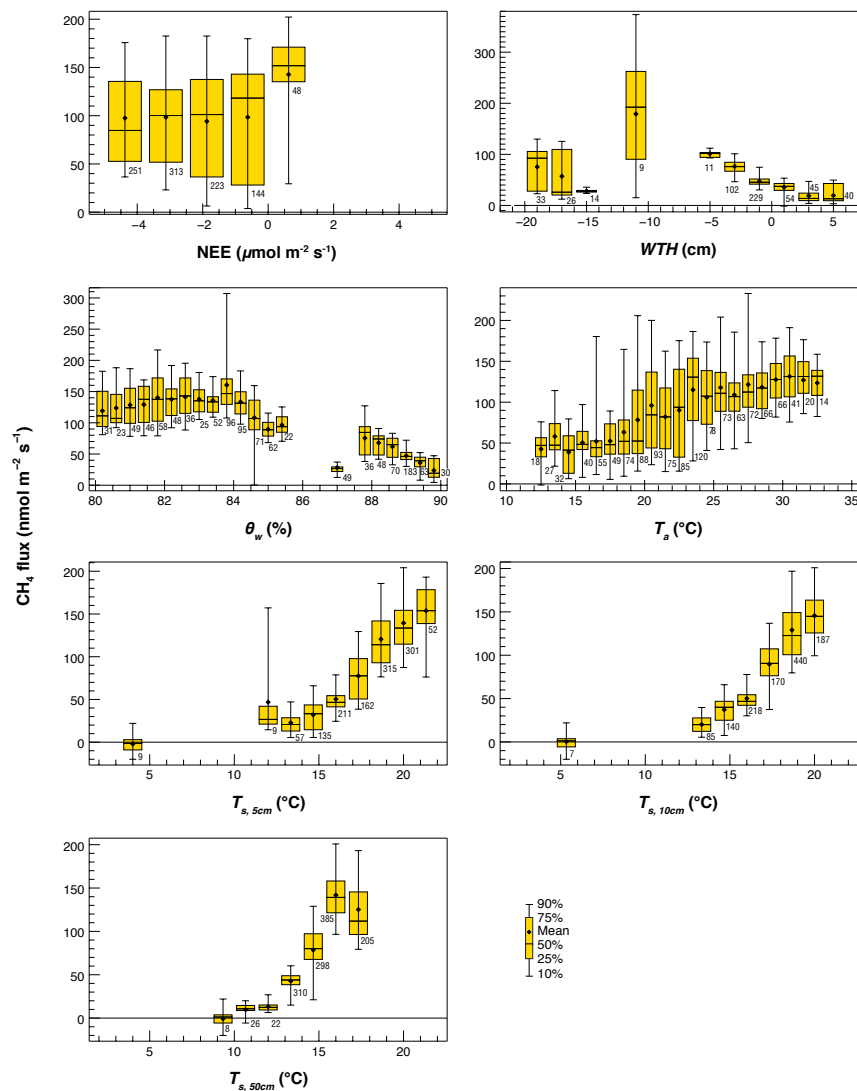
“CH₄ fluxes with quality flags 0 and 1 according to Mauder and Foken (2004) were plotted against all relevant variables
including NEE, *WTH*, θ_w , T_a , $T_{s,5cm}$, $T_{s,10cm}$, and $T_{s,50cm}$. The highest correlation between a single variable and the CH₄ flux
1105 was found for soil temperature using an exponential relationship (Fig. S3). Of the soil temperatures measured at three
different depths, $T_{s,10cm}$ explained the highest proportion of the variance in CH₄ flux (Table S1). Therefore, $T_{s,10cm}$ was used
to build an initial model and a logarithmic transformation of the CH₄ fluxes was applied to remove the heteroscedasticity and
permit the use of a linear regression model. Then the residual analysis was applied to explore whether the variance in the
residual could be explained by other controls. The residual was defined as the ratio of the measured CH₄ fluxes to the
1110 modelled CH₄ fluxes from the initial model. Based on the residual analysis, the main contributor to the residual, *WTH*,
explained 7% of the variance (Table S2). Additionally, there was a hysteresis relationship between CH₄ flux and *WTH* (Fig.
S4). In order to have a more robust gap filling model, $T_{s,10cm}$ and *WTH* were used to fill the gaps in CH₄ fluxes. We used a
combination of an exponential temperature response function and a linear *WTH* function as follows:

1115

$$F_m = (aWTH + b)e^{cT_{s,10cm}} \quad (3)$$

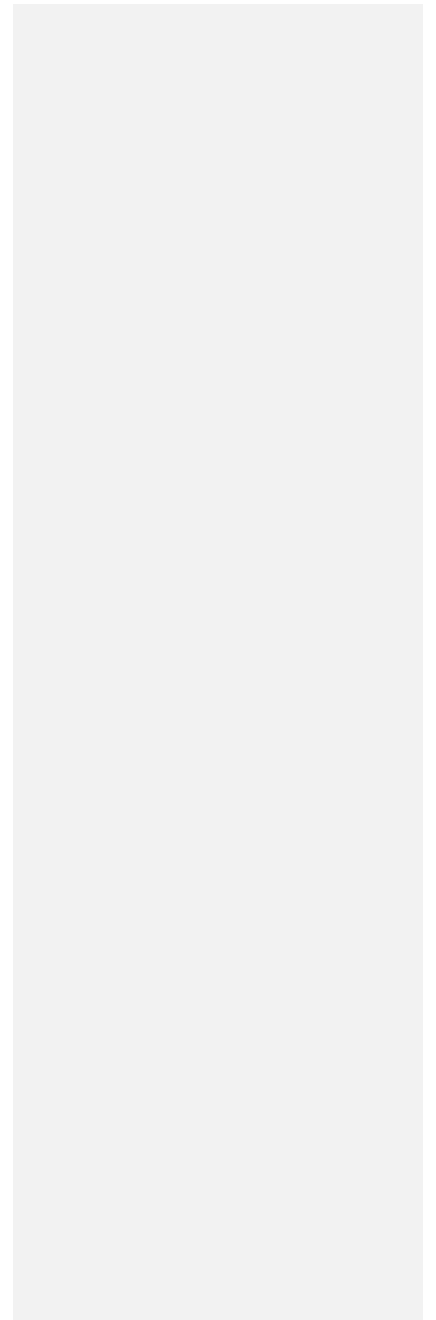
where a , b , and c are time-varying empirical parameters. The three parameters were fitted separately for each day, using a moving window of ± 105 days using all data from the study period when friction velocity was greater than 0.08 m s^{-1} . Overall, 76% of the variance of the CH_4 fluxes was explained by $T_{s,10cm}$ and WTH . The combination of soil temperature and WTH has also been shown to explain a large proportion of the observed variances in CH_4 fluxes in peatlands in other studies (Brown et al., 2014; Goodrich et al., 2015).”

Second, two new figures (Fig. S3 and S4) and two tables (Table S1 and S2) have been added in supplementary material:



1125 Figure S3. The relationships between CH₄ fluxes with quality flags 0 and 1 and all measured environmental factors using all

half-hourly data.



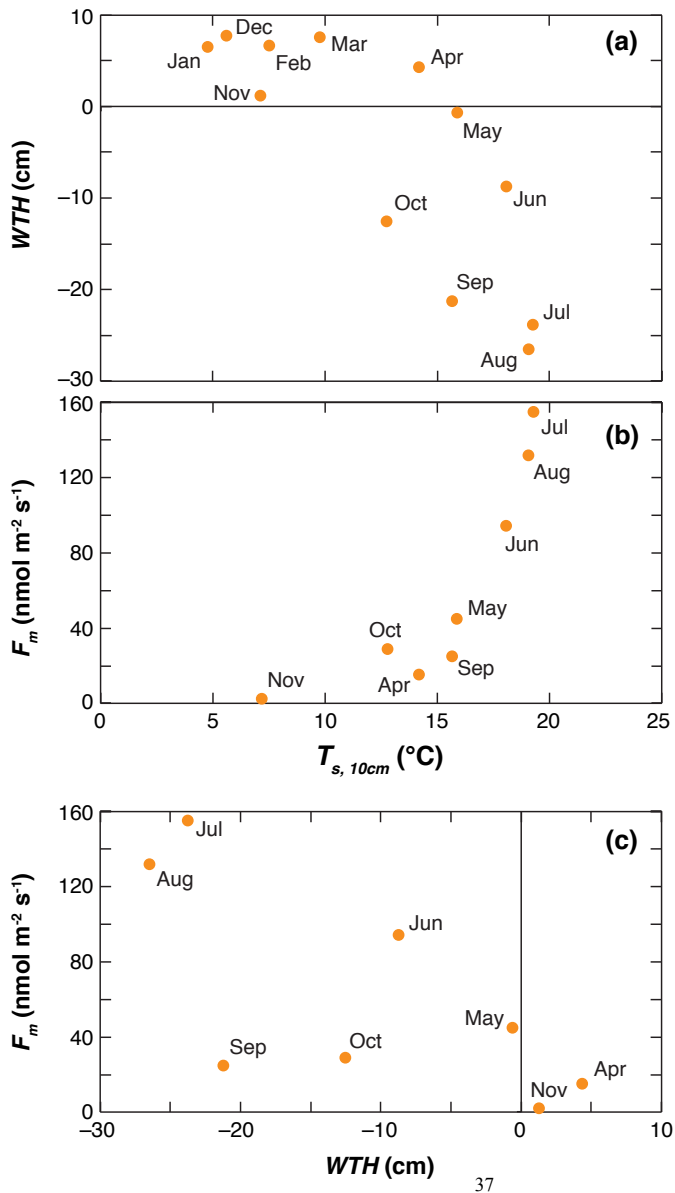


Figure S4. (a) Monthly mean WTH vs. monthly mean $T_{s,10cm}$. (b) Monthly mean CH_4 flux based on available measurements
1130 (non-gap-filled) vs. monthly mean WTH and (c) $T_{s,10cm}$.

Table S1. Coefficients of determination (R^2) from simple regression analyses of relationships between CH_4 fluxes and soil temperature (T_a , $T_{s,5\text{cm}}$, $T_{s,10\text{cm}}$, $T_{s,50\text{cm}}$, θ_w , WTH and NEE. The highest value was marked as orange.

Initial identification of major controls							
Variables \ Functions	$T_{s,5\text{cm}}$	$T_{s,10\text{cm}}$	$T_{s,50\text{cm}}$	T_a	θ_w	WTH	NEE
Linear	0.55	0.59	0.48	0.21	0.57	0.55	0.00
Exponential	0.66	0.73	0.64	0.23	0.51	0.51	0.01
Logarithmic	0.50	0.54	0.48	0.28	0.50	0.00	0.00
Polynomial	0.56	0.61	0.48	0.31	0.57	0.52	0.01

1135 Table S2. The residual analysis for T_a , θ_w , WTH and NEE for the study period based on the relationship between CH_4 flux
 $T_{s,10\text{cm}}$. The highest value was marked as orange.

	NEE	WTH	θ_w	T_a
R^2 value	0.004	0.065	0.045	0.022

1140 Finally, the monthly CH_4 fluxes and annual CH_4 budget were re-calculated using the soil temperature at 10 cm compared to
 5 cm in the discussion paper. This resulted in a change of the annual CH_4 flux from 16 to 17 g $\text{CH}_4\text{-C m}^{-2} \text{ year}^{-1}$. Also CO_2
 fluxes were recalculated. The corresponding text has been updated (Line 32, 360, 362, and 393).

SPECIFIC COMMENTS TO THE AUTHOR(S)

1145 **1) Throughout: “eddy-covariance” should be “eddy covariance”. The hyphen is unnecessary.**

[Response]

This has been changed as proposed.

1150 **2) Line 1 of abstract: peatlands have been drained for many other purposes that have also changed them into C sources.**

[Response]

This sentence has been edited as follows:

“Many peatlands have been drained and harvested for peat mining, **agriculture, and other purposes**, which has turned them from carbon (C) sinks into C emitters.”

1155

We also changed the text on line 50:

“Many peatlands have been harvested and continue to be disturbed by the extraction of peat for horticultural use **and conversion to agriculture as well as other purposes.**”

1160 **3) Introduction and lines 38-40. I suggest that the authors might consider constraining their introduction (or at least detailed examples of fluxes) to peatlands. Wetlands are so incredibly diverse that it is almost meaningless to provide context for a study focused on a restored peatland. The Grasset et al. (2016) paper seems a rather strange choice because this appears to have been an aquatic study and not even focussed on annual fluxes. I couldn’t find the CO₂-C values cited in this or the Mitsch et al. (2013) papers. It is really important at this stage of a manuscript that the authors concentrate on verifying their source material and providing relevant and authoritative literature sources.**

1165

[Response]

We have followed the reviewer’s advice and focused on peatlands. We agree selected the wetlands were not comparable. The first paragraph of introduction has been re-written as follows:

1170 **“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; Mitsch et al., 2010) but 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 (Bridgham et al., 2006; Lal, 2008; Wisniewski and Sampson, 2012). On the other hand, they emit significant quantities of methane (CH₄), a powerful greenhouse gas (GHG), which is responsible for 30% of all global CH₄emissions (Bergamaschi et al., 2007; Bloom et al., 2010; Ciais et al., 2013) due to anaerobic microbial decomposition (Aurela et al., 2001; Rinne et**

1175

al., 2007). Peatlands are the most widespread of all wetland types in the world representing 50 to 70% of global wetlands (Roulet, 2000; Yu et al., 2010. Peatlands around the world sequester around 50 g CO₂-C m⁻² year⁻¹ (Roulet et al., 2007; Christensen et al., 2012; Humphreys et al., 2014; McVeigh et al., 2014; Peichl et al., 2014, Pelletier et al., 2015) and emit around 12 g CH₄-C m⁻² year⁻¹ (Abdalla et al., 2016; Brown et al., 2014; Jackowicz-Korczynski et al., 2010; Lai et al., 2014; Urbanova et al., 2013). Furthermore, it has been shown that it is crucial to include peatlands in the modelling and analysis of the global C cycle (Frolking et al., 2013; Kleinen et al., 2010; Wania et al., 2009).”

4) Line 73 onward. Using the term “long-term” suggests multi-year. Clearly this paper is not multi-year so, at least in the conclusion, the authors might need to acknowledge the additional uncertainties affecting their conclusions caused by there being a single year of study.

[Response]

We appreciate reviewer’s comments. We have changed this to “year-round” for clarity.

5) Lines 130-131. The change to the 60 Hz detail has not been made.

[Response]

We appreciate the reviewer noticing our slip here. The change has now been made.

6) Line 146. “Small gaps ... and H₂O fluxes”?

[Response]

This information has been added as follows:

“Small gaps (<60 minutes) of missing CO₂, H₂O, and CH₄ fluxes were filled by linear interpolation.”

The gap filling method for larger gaps in H₂O fluxes has also been added as mentioned in our response to Comment #27.

7) Line 154 “atmosphere” is mis-spelled.

[Response]

We have corrected the spelling error.

8) Use of terms F_c and NEE. In general there is inconsistent use of these terms which, to an unfamiliar reader, might be very confusing. For example, why on line 155 use “NEE and F_m” rather than “F_c and F_m”?

[Response]

We appreciate reviewer’s suggestion. We decided to delete F_c in the manuscript and figure captions for clarity.

9) Lines 167-168. It is not really accurate to state that the parameters “were determined separately for each day of the year”, when the dataset for each day consisted of a window of 120 days width! Consider a more accurate description.

[Response]

We appreciate reviewer’s comment. This is a misunderstanding, the moving window was 120 days for R_e , but for each day the parameters were determined independently using a ± 60 -day moving window centered on that day. We have edited the text for clarity at line 168 and 181 as follows:

1215 “... the height of plateau phase. For each day of the year, the parameters r_1 , r_2 , and r_3 for R_e were determined independently using a moving ± 60 -day window centered on that day based on all ...”

1220 “... was fixed at 0.7 (Farquhar et al., 1980). For each day of the year, the time-varying parameters MQY and P_M were determined independently using a moving ± 45 -day window centered on that day using all data from 2014 to 2016 when friction velocity was ...”

10) Lines 173-182. This does not actually describe completely how GEP was modelled. The first step, surely, was to partition GEP out from measured values of NEE (using modelled R_e), and then the light response function was fitted.

[Response]

1225 We appreciate reviewer’s comments. This information has been added as follows (at line 174):

“GEP was first partitioned from measured daytime NEE using modelled R_e . Any missing GEP data were then modelled using the photosynthetic light-response curves (Ögren and Evans, 1993) based on ...”

11) Line 207. Include reference to (the new) Fig. 2.

1230 [Response]

This has been implemented as follows (at line 210):

“The study site received a total annual precipitation of 1062 mm, of which 16% (174 mm) fell during the warm half year (Apr-Sep) and 84% (888 mm) during the cold half year (Oct-Mar) (Fig. 2).”

1235 12) Line 246. “Despite...”. It is not quite clear what this sentence means. Maybe replace with “Compared to ...”.

[Response]

This has been implemented as follows:

“~~Despite~~ Compared to a large seasonal amplitude in monthly GEP, R_e showed less variability over the year.”

1240 13) Line 247. This should be a reference to Fig. 3, not Fig. 4.

[Response]

Thanks for pointing out the error. We have corrected the reference.

1245 **14) Line 264. Replace “pristine” with “more or less pristine”. For example, the Campbell et al. (2014) study was for a drainage impacted peatland. It is hard to judge what “pristine” actually means, and so most wetland scientists will avoid the term.**

[Response]

We appreciate reviewer’s suggestion. The word, “undisturbed”, has been implemented to avoid the controversy as follows:
“Values that are comparable to the current restored wetland were reported in five **undisturbed** temperate wetlands: ...”

1250 **15) Lines 277-281. There needs to be some details provided about the methodology used to calculate DOC fluxes, since the reference is unpublished. At least it is nice to see some uncertainty value provided!**

[Response]

1255 We appreciate reviewer’s comment. This work is not yet peer-reviewed, but has been published and is accessible through AGU 2016 (<https://agu.confex.com/agu/fm16/meetingapp.cgi/Paper/165988>) where the complete poster contribution describing the method is also available. To provide some context though, we have added some information regarding to the methodology used to measure DOC fluxes as follows (at line 282):

“Estimation of DOC fluxes was based on regular (approx. monthly) water samples collected at 5 locations within the flux tower footprint using the headspace equilibration technique. Lateral flow was estimated as the residual of the water balance.”

1260 **16) Line 284. Where is the “daily maximum in GEP” shown?**

[Response]

This specific number was calculated. It is not shown in the figure. Please note that the full dataset of this study will be made available at the time of publication in a data repository.

1265 **17) Lines 286-287. “The rapid decrease in monthly R_e (Figure 3?) from May to June ...”. Fig. 3 does not support this statement.**

[Response]

1270 We appreciate reviewer’s suggestion. Figure 3 shows this change too, but in order to be clear, a reference to Table 1 which best shows this decrease has been added as follows:

“The rapid decrease in monthly R_e from May to June (**Table 1**) was caused by ...”

1275 **18) Lines 319-321. How were these controls investigated? How did you determine “the effects of Ta on GEP were approximately limited between 10 and 15 C.”? (The underlined words make no sense!) It is notoriously difficult to isolate the effects of temperature versus light quality versus VPD, because they are all strongly correlated.**

[Response]

We appreciate reviewer’s comments. These two variables (WTH and T_a) were plotted against gap-filled GEP to let us investigate their effects on NEE. To clarify this, we rewrote this short paragraph as follows:

1280 “Other possible controls on GEP explored were WTH and T_a . We found that WTH was not a control on GEP ($R^2 = 0.08$) in the current study as the study area remained fairly wet throughout the year. Furthermore, the effect of T_a on GEP was less and limited to a smaller temperature range, compared to T_s . ~~approximately limited between 10 and 15 °C.~~”

19) Line 326. Still using the inaccurate term “significant”. Do you mean “Much larger”?

[Response]

1285 We appreciate reviewer’s suggestion and apologize for not making the change. The change has been made as follows:

“..., and then became a ~~much larger significant~~ source in summer ...”

20) Lines 328-329. Hysteresis in the Ta vs Fm relationship is hinted at. This suggests that the simplistic gap filling method might be quite inaccurate at these times.

1290 [Response]

The reviewer has made an important point. In order to explore a possible hysteresis effect, we analyzed the dataset further by plotting the monthly (not gap filled) CH_4 flux vs. $T_{s,10cm}$ and also WTH (Fig. S2, or please refer to our response to Comment #2 in the major comment section). We also graphed monthly $T_{s,10cm}$ vs. WTH which shows that a hysteresis effect is observed, as WTH and $T_{s,10cm}$ are shifted in phase. Based on these additional analyses, we have updated the CH_4 gap filling model to include both, $T_{s,10cm}$ and WTH, and added a short paragraph to discuss the possible reasons for the seasonality of CH_4 fluxes (see our answer to Comment #25 below). Thus we have deleted the sentence under reference to avoid any misunderstanding.

1295

~~“ CH_4 fluxes showed a seasonal pattern, which was linked to phenology and temperature.”~~

1300 **21) Lines 346-347. Why is this surprising when it has been reported by many other studies?**

[Response]

We appreciate reviewer’s question. This part has been re-written for clarity as follows:

“Surprisingly, there was only a small diurnal variation observed for CH_4 fluxes in the summer months, ~~while larger diurnal variations have~~ been found in other studies (Juutinen et al., 2004; Long et al., 2010; Sun et al., 2013; Wang and Han, 2005).”

1305

22) Line 365. "... magnitude of fluxes changed differently ..." is fairly meaningless. What do you mean?

[Response]

1310 We appreciate the comment. As we explained in the previous lines (362 – 365), the early onset of CO₂ sequestration caused the most negative net GHG forcing from April to June; the subsequent rapid drop in CO₂ sequestration and lagged CH₄ fluxes led to the highest net GHG forcing in July and August.

23) Lines 366-367. Why should they be expected to be representative?

[Response]

1315 We appreciate reviewer's point. If the climate is steady or the effects of environmental variables are small, measuring the fluxes in the growing season, which is the time with least gaps due to sufficient solar charging, would be sufficient to provide a reasonable estimate of the annual budget. Moreover, we want to emphasize that a short-term campaign can be a good way to identify important site processes but the determination of the annual budget requires reliable long-term measurements. Thus, we have edited the text from Line 366 to 367 for clarity as follows:

1320 "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; a short-term campaign can be a good way to identify important site processes but the determination of the annual budget requires reliable long-term measurements."

24) Lines 368-371. This paragraph is a very weak response to Reviewer 1's comment. It is barely coherent. It does not address the long-term nature of C accumulation (from CO₂) in wetlands vs the short lifetime of CH₄ in the atmosphere.

[Response]

1330 We appreciate reviewer's comments. We have addressed the point by pointing out that actual radiative forcing from sustained CO₂ and CH₄ fluxes are not included in GWP in the last version.

25) Line 383. It is surely unusual that there is such a huge seasonal variation in F_m, especially given the temperate climate and high water table in winter. Can the authors suggest why this might be the case? The proper place for this is in Section 4.4.1.

[Response]

1335 We appreciate reviewer's comments. We have added a short paragraph at the end of the first paragraph in Section 4.4.1 which discusses the possible reasons for this as follows:

"Although it has been suggested that in some peatlands, WTH acts as a main control on CH₄ fluxes (Drösler et al., 2008; Knorr et al., 2009; Romanowicz et al., 1995; Roulet et al., 1993; Windsor et al., 1992), it has also been found that CH₄

1340 emissions from wet soils (where the water table fluctuates within a small range near the surface) are highly dependent on T_s ,
because the oxidation in a shallow top soil is negligible (Jackowicz-Korczynski et al., 2010; Long et al., 2010; Olson et al.,
2013; Rinne et al., 2007; Song et al., 2009). In our study, CH₄ emissions in the summer months were relative high even when
the water table dropped to around 20 cm below the surface, likely because the peat maintained anaerobic conditions above
the water table (as discussed in Hendriks et al., 2007). In addition, one needs to consider the transport pathways for CH₄
1345 which may help explain the higher CH₄ fluxes in summer. First, the presence of sedges created an effective additional
diffusion pathway for CH₄ through the plants' aerenchyma (Herbst et al., 2011; Treat et al., 2007). Second, a high water
table especially when it rises above the soil surface increases the diffusion resistance to CH₄ transport (Brown et al., 2014;
Walter and Heimann, 2000). An additional reason for the lowest CH₄ emissions occurring in winter months could be the
suppression from rain events (Goodrich et al., 2015) as 84% of rain fell at the site during the cold half-year.”

1350 **26) Line 387. If the flux of DOC is taken into account, the annual C sink strength is less than this.**

[Response]

We appreciate reviewer's comments. We have re-written this sentence for clarity as follows:

“In terms of the C balance (DOC fluxes excluded), our results suggest that our study area in BBCEA was a net C sink ...”

1355 **27) Figure 2. Caption does not mention ET. Was it measured at the site and gapfilled or is it estimated from climate
station values?**

[Response]

We appreciate reviewer's question. ET has been added to the caption, and the text describing the gap filling method for H₂O
fluxes has been added in Section 3.3 on line 149 as follows:

1360

“Longer gaps in H₂O fluxes were filled with the online tool developed by the Max Planck Institute for Biogeochemistry in
Jena, Germany. This tool uses the look-up table method documented in Falge et al. (2001) and Reichstein et al. (2005).”

28) Figure 3 caption. The x-axis label (F_CO2) has not been corrected.

1365 [Response]

We appreciate the reviewer noticing this. The version of figure was incorrect, it has been replaced by the correct one.

29) Figure 7 caption is inadequate. Insert “Ensemble”. Note that mainly summer is represented.

[Response]

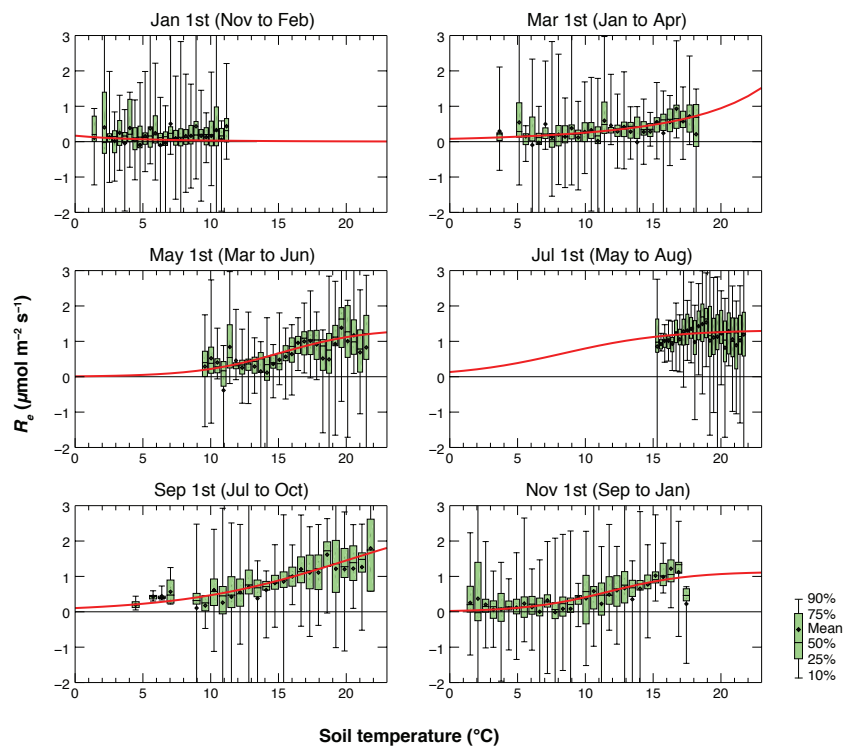
1370 We appreciate reviewer's suggestion. The information has been added as follows:

“The ensemble diurnal course of measured CH₄ fluxes from the EC-2 system during the study period. More datasets were
available from the summer half-year than from the winter half-year.”

30) Figure S3. It would be preferable to use a common x-axis scale on all of these panels (as was done for Fig S4).

1375 [Response]

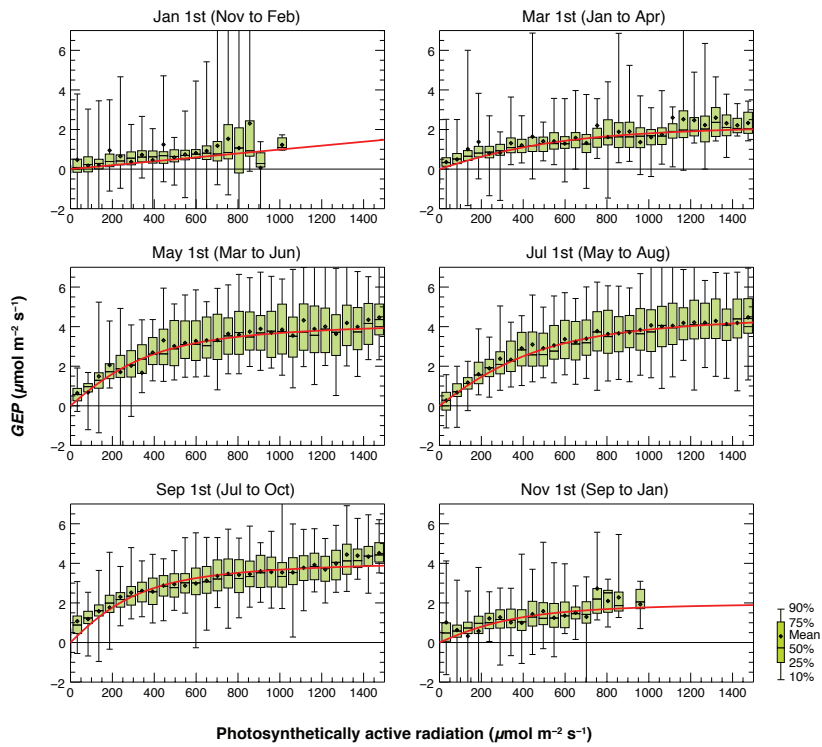
We appreciate reviewer's comments. This change has been implemented as follows:



1380 31) Figures S3 and S4. It is still a little confusing what “on the first day of each time period” means. Presumably this is the function derived for the first day of the period – which is actually derived from data sourced 60 days prior to 60 days after. Surely it would make more sense to choose a day close to the center of the time period.

[Response]

We appreciate reviewer’s comments. This subtitle of each figure has been edited for clarity as follows:



1385