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 suppressed 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 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; Mitsch et al., 2010), but they act as a major sink for the long-term C storage by sequestering carbon dioxide (CO_2) from the atmosphere. For example, strong C sinks (896 to 1139 g CO_2-C m^{-2} yr^{-1} and 1236 g CO_2-C m^{-2} $year^{-1}$) were found in Southeast USA and Eastern France, respectively (Grasset et al., 2016; Mitsch et al., 2013). Other wetlands around the world sequester around 100 g CO_2-C m^{-2} $year^{-1}$ (Bortolotti et al., 2016; Lu et al., 2016; Petrescu et al., 2015). 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). However, wetlands emit significant quantities of methane (CH_4), a powerful greenhouse gas (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 (Bergamaschi et al., 2007; Bloom et al., 2010; Ciais et al., 2013). 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). Their dynamics have played an important role in the global C cycle during the Holocene period (Gorham, 1991; Menviel and Joos, 2012; Yu, 2011), and 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).

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 increases the risk of peatland fires, which could consequently cause 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 other studies, 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).

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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 (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 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 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 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 (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 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 ℃ and average annual precipitation was 1189 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 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 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. A soil volumetric water content (θ_v) sensor (CS616, CSI) was inserted vertically to measure integrated θ_v from the surface to a depth of 0.30 m.

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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 (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 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 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 the climate data (<1% of the year) were filled using measurements at nearby climate stations. Small gaps (<60 minutes) of missing CO_2 and CH_4 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). In this study, net fluxes of CO_2 and CH_4 toward the ecosystem surface are negative and net fluxes from the ecosystem surface to the stmosphere are positive. Therefore, negative NEE and F_m represent net CO_2 and CH_4 uptake, respectively.

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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 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. 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 226 and 245 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:

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$$F_m = ae^{bT_{s,5cm}} \tag{3}$$

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:

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

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 (44.01 g mol^{-1}), and m_{CH_4} is the molecular mass of CH_4 (16.04 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 (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 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 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. 3, 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).

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Despite 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. 4). 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).

The annual NEE in this study was more negative than in the majority of previously reported NEE values for pristine temperate peatlands, which were weak sinks, typically in the range of -50 g C m^{-2} $year^{-1}$ (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 g C m^{-2} $year^{-1}$ (Lafleur et al., 2001), −234 g C m^{-2} $year^{-1}$ (Campbell et al., 2014), -210 g C m^{-2} $year^{-1}$ (Fortuniak et al., 2017), −189 g C m^{-2} $year^{-1}$ (Flanagan and Syed, 2011), and −103 g C m^{-2} $year^{-1}$ (Lund et al., 2010). The few datasets in the literature for NEE of restored wetlands showed a wide range of values. Some were CO_2 sources, with NEE ranging from +103 g C m^{-2} $year^{-1}$ to +142 g C m^{-2} $year^{-1}$ (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 g C m^{-2} $year^{-1}$ to -270 g C m^{-2} $year^{-1}$ (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 g C m^{-2} $year^{-1}$ (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

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a marsh of 23 ± 13 g C m^{-2} year^{-1}. D'Acunha et al. (2016) estimated DOC export for the current study area for Jan – Dec 2016 to be 22.4 g C m^{-2} year^{-1} (15% of annual NEE).

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. 4. The daily maximum in GEP changed with season resulting in the high magnitude of NEE during midday between May and July (~ -3.5 µmol m^{-2} 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 µmol m^{-2} s^{-1} for most of the study period. The rapid decrease in monthly R_e from May to June 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 $T_{s,5cm}$ 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, due to general warm condition (>15°C), R_e remained nearly constant at ~1 µmol m^{-2} 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 $T_{s,5cm}$. 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. The role of WTH was described above and T_a had 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.

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4.3.4 Gross ecosystem productivity

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. 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. 3, 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 WTH and T_a. We found that WTH was not a control on GEP in the current study as the study area remained fairly wet throughout the year. Furthermore, the effects of T_a on GEP were approximately limited between 10 and 15 ℃.

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}). Seasonally, it was a weaker 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.

The annual CH_4 flux in this study area was lower than CH_4 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, CH_4 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 CH_4 flux from a restored wetland in Denmark that was lower than in this study (9 to 13 g CH_4-C m^{-2} year^{-1}). Our annual CH_4 flux at 16 g CH_4-C m^{-2} year^{-1} was comparable to an average natural temperate wetland CH_4 flux, which is typically around 15 g CH_4-C m^{-2} year^{-1} (Abdalla et al., 2016; Fortuniak et al., 2017; Nicolini et al., 2013; Turetsky et al., 2014). The CH_4 fluxes from a number of temperate and tropical pristine wetlands exceeded the CH_4 fluxes reported in this study, including emissions from marshes in the Southwestern US (130 g CH_4-C m^{-2} year^{-1}, Whiting & Chanton, 2001), tropical wetlands in Costa Rica (82 g CH_4-C m^{-2} year^{-1}, Nahlik & Mitsch, 2010), and

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marshes in the Midwestern US (50 g CH_4-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 CH_4 fluxes

The ensemble diurnal courses of the CH_4 fluxes measured by the EC-2 system are shown in Fig. 7 from 16th June 2015 to 15th June 2016. Surprisingly, there was only small diurnal variation observed for CH_4 fluxes in the summer months, as has 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 CH_4 transport, which masked the diurnal pattern of CH_4 fluxes. Furthermore, $T_{s,5cm}$ appeared to be the main environmental control on CH_4 fluxes in this study but did not have as strong effect on CH_4 emissions as found in previous studies. Thus CH_4 was continuously emitted at a similar rate during daytime and nighttime. From January to March and October to December, the winter half-year, 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 of soil temperature and may be partly due to convective turbulent mixing caused by cooling during the evening (Godwin et al., 2013).

4.5 CO_2e exchange

Figure 8a and 8b 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 in terms of CO_2e, 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.

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 CO_2 and CH_4 fluxes can not be evaluated) and alternative models were proposed (Frolking and Roulet, 2007; Fuglestvedt et al., 2000; Neubauer and Megonigal, 2015; Petrescu et al., 2015; Smith and Wigley, 2000).

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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.

Acknowledgements

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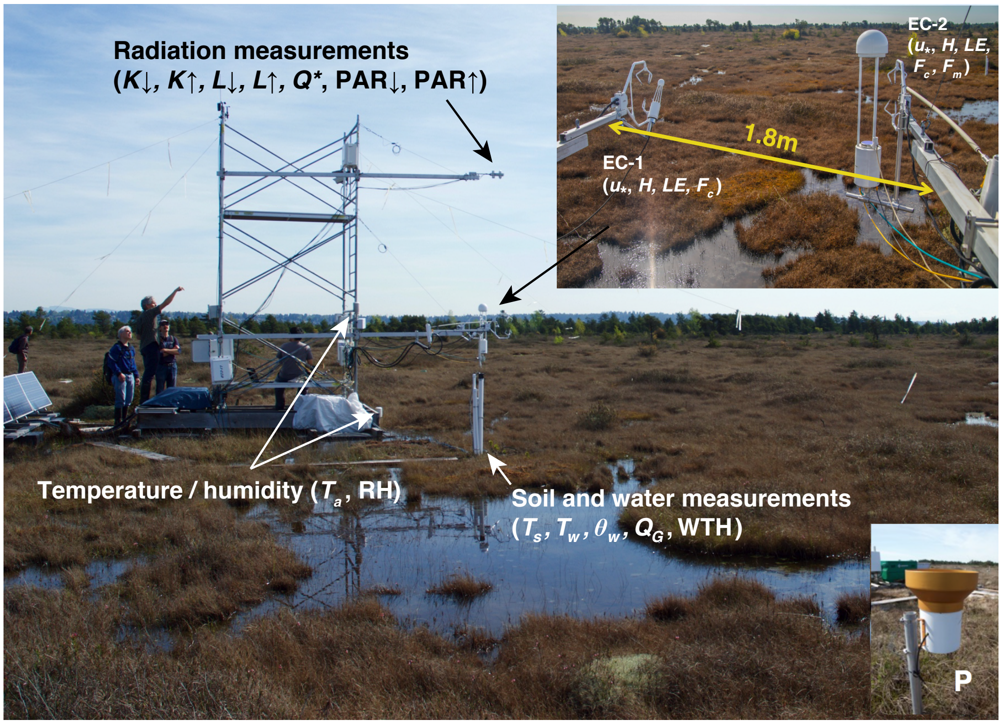

Figure 1: Flux tower on floating platform with EC-1 and EC-2 systems facing south and instruments that measured climate variables indicated (friction velocity (u_*), sensible heat flux (H), latent heat flux (LE), CO_2 flux (F_c), CH_4 flux (F_m), incoming shortwave radiation (K ↓), outgoing shortwave 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 height (WTH), and precipitation (P)).

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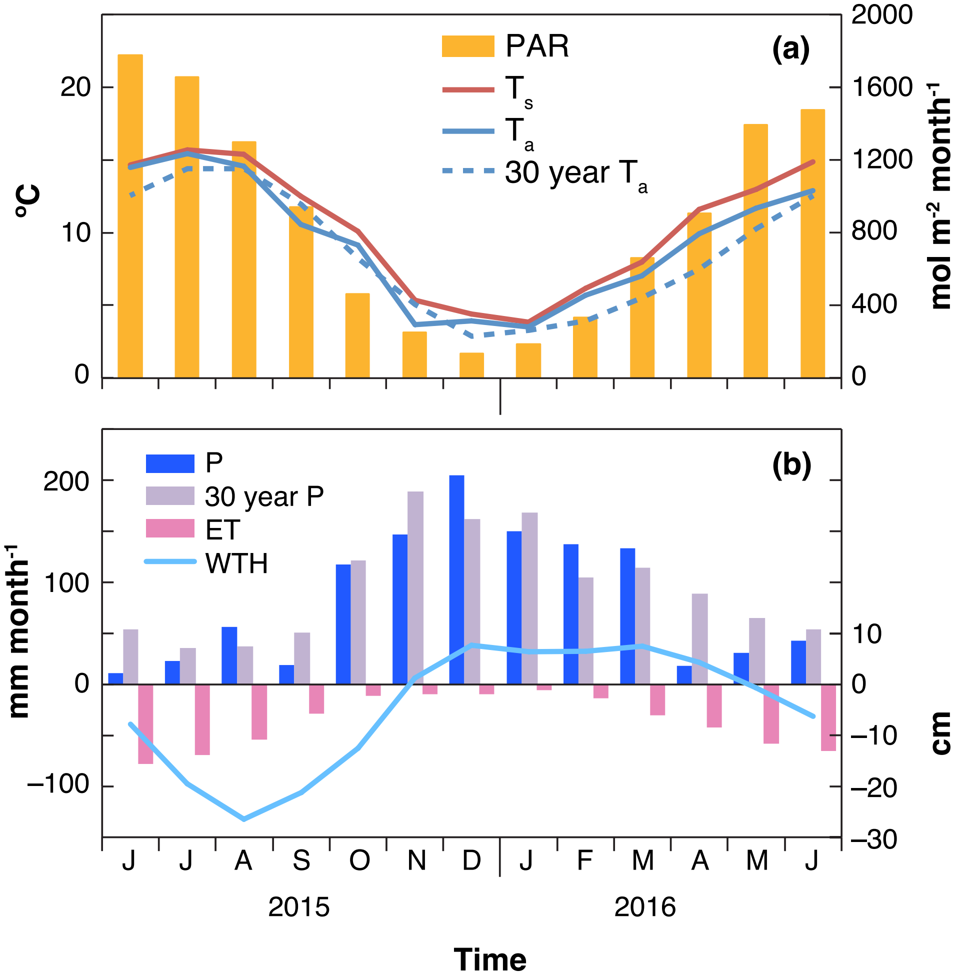

830 Figure 2: The annual course of weather variables (T_a, T_s, P, and PAR) and WTH. The 30-year climate normals (30-year T_a and P) were measured at Vancouver International Airport (Data: Environment Canada).

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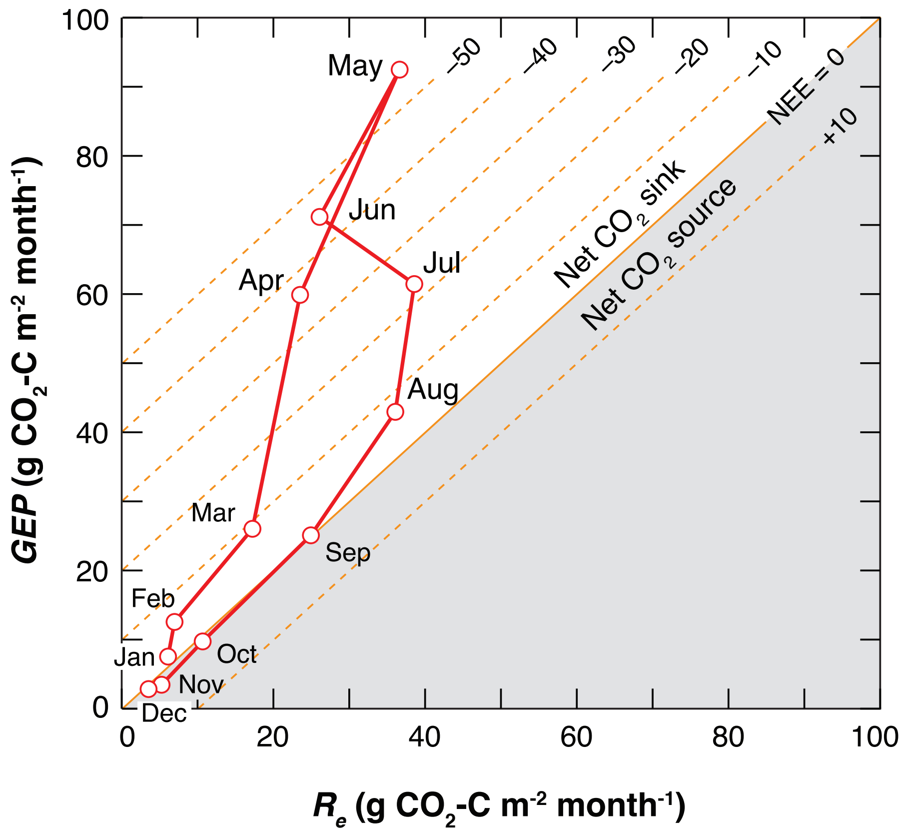

Figure 3: Monthly gap-filled R_e (x-axis) drawn against GEP (y-axis). The resulting NEE can be read off the diagonal lines. The thick 1:1 line shows carbon neutrality, while lines in the upper right are of increasingly negative NEE (uptake) and lines towards the lower right are positive NEE (net source).

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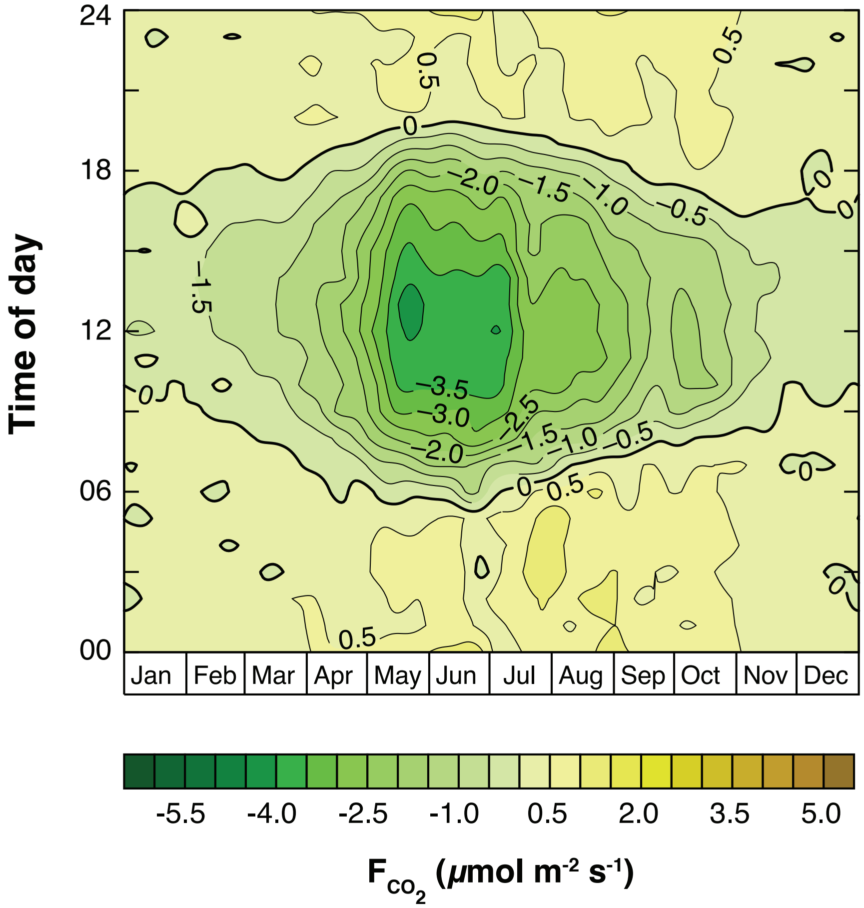

Figure 4: Isopleths of gap-filled NEE (net CO_2 fluxes) from the EC-1 system plotted as a composite in the study year. The
840 graph uses a Gaussian filter of σ = 45 days (which conserves total NEE) to graphically smooth horizontal variations.

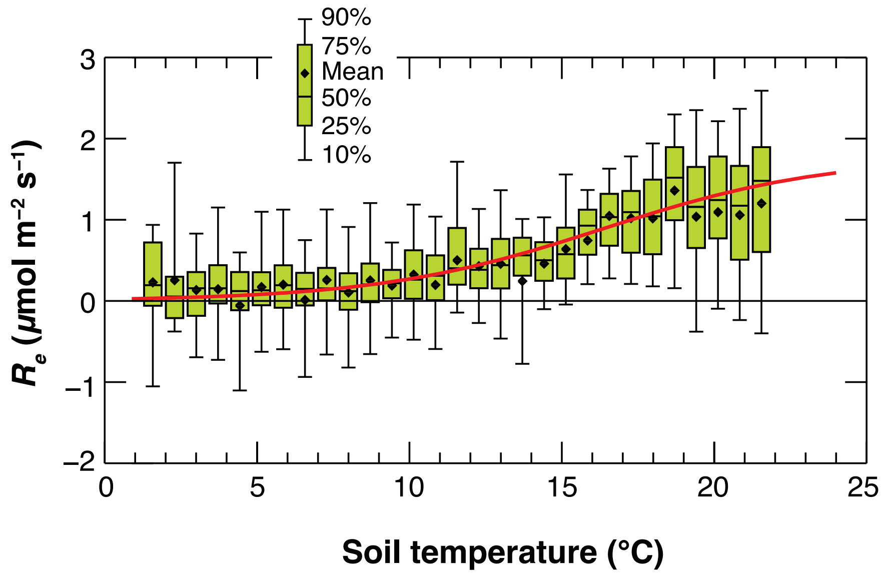

Figure 5: Relationship between R_e (nighttime 30-minute CO_2 flux measurements) and $T_{s,5cm}$ during the entire study period. The u_* threshold was 0.08 m s^{-1}. The fitted curve is a logistic relationship following Eq. 1. $T_{s,5cm}$ was binned for 32 classes from minimum of $T_{s,5cm}$ to maximum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

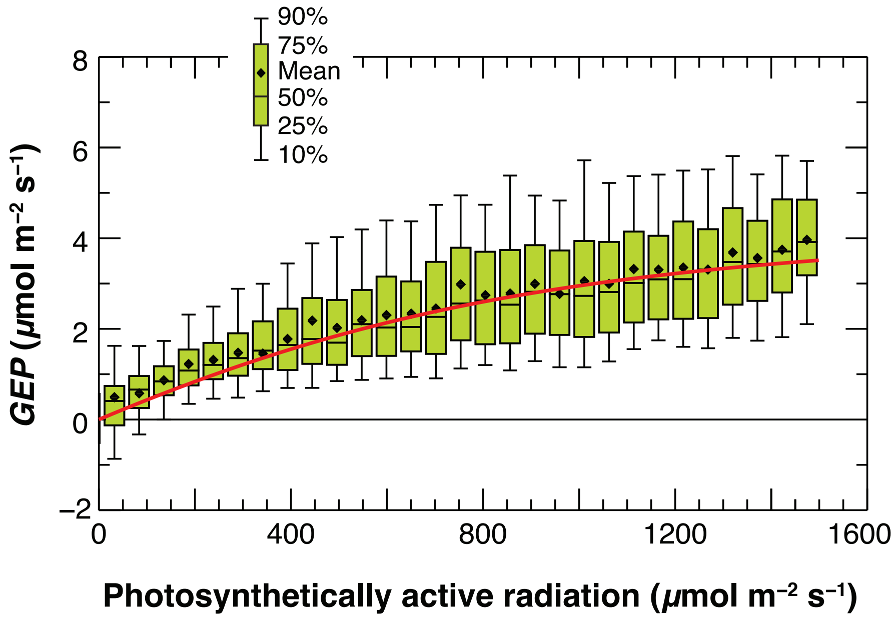

Figure 6: Annual light response curve determined from the daytime 30-minute NEE measurements and Eq. 1, i.e., GEP = R_e + -NEE. The curves are the best fit of the Eq. 2. PPFD was binned for 30 classes from 0 to 1500 µmol m^{-2} s^{-1}. Annual *MQY* was 4.00 mmol C mol^{-1} photons, P_M was 4.68 umol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

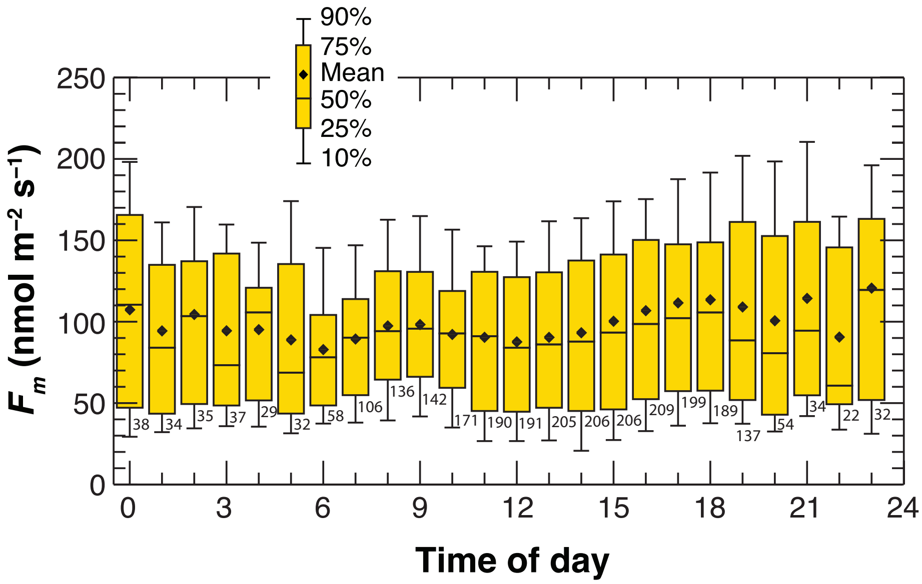

Figure 7: Diurnal course of measured CH_4 fluxes from the EC-2 system during the study period.

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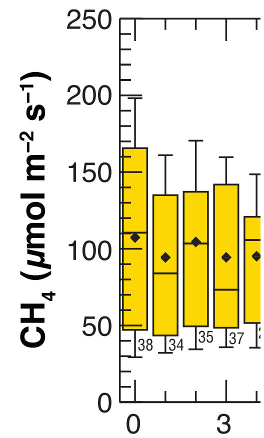

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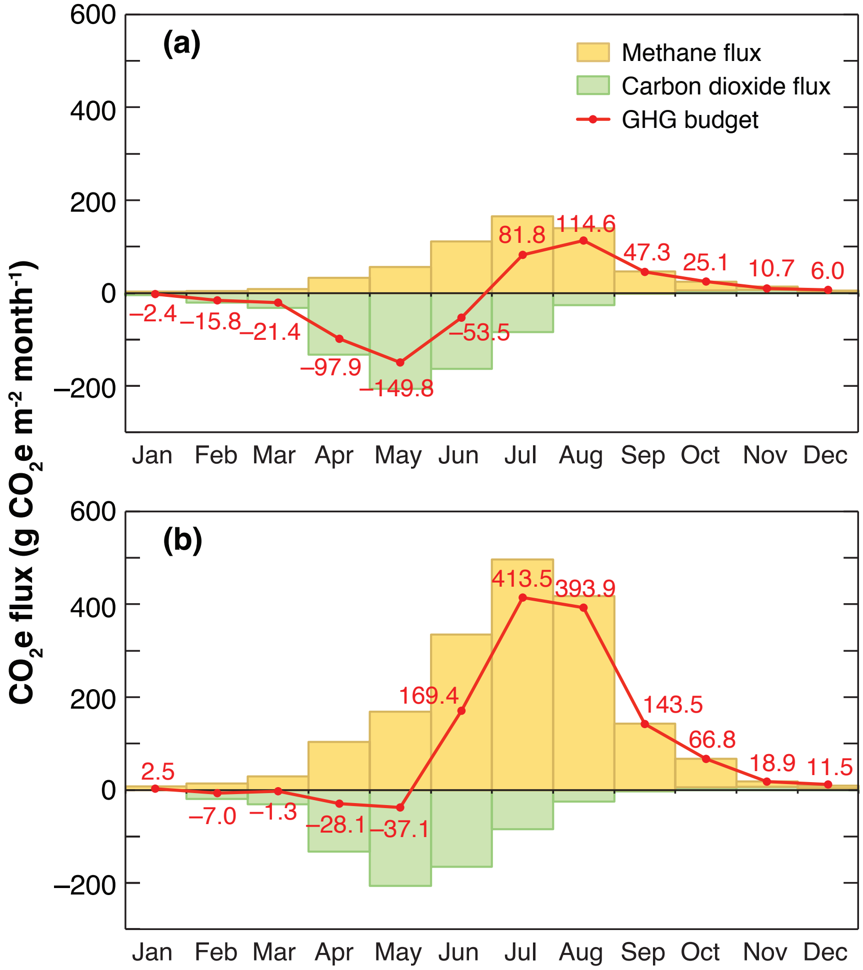


860 Figure 8: EC-measured monthly CO_2, CH_4 and net GHGs fluxes shown as CO_2e totals by using (a) 100-year and (b) 20-year GWPs. Missing data were gap-filled.

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	GEP	NEE	CH_4 fluxes	20-year CO_2e fluxes	100-year CO_2e fluxes
	(g CO_2-C m^{-2} $month^{-1}$)			(mg CH_4-C m^{-2} $month^{-1}$)	(g CO_2e m^{-2} $month^{-1}$)	(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	g CO_2-C m^{-2} $year^{-1}$			g CH_4-C m^{-2} $year^{-1}$	g CO_2e m^{-2} $year^{-1}$	
year	236	415	-179	16	1147	-55

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%

870 [*] Site identifier in global FLUXNET database (http://fluxnet.ornl.gov).
[+] Data from Krishnan et al., 2009 before fertilisation.

REFEREE COMMENTS:

We greatly appreciate all comments from the reviewers. These detailed comments have greatly improved the quality of the manuscript.

Referee #1

MAIN COMMENTS TO THE AUTHOR(S)

1) Estimation of the results uncertainties. The authors estimate the sensitivity of the results on windows size (for Re and GEP). It would nice to estimate the range of results for different gap filling strategies (e.g. neural network) and finally express the annual budget of CO2 in the form NEE= -179±??? g CO2-C m-2 year-1 and similarly for CH4 flux (or at least discuss on the base of recent publications which consider such impact).

[Response]

We appreciate the comments of the referee. The major uncertainties in the annual estimates of GEP, R_e, NEE, and CH_4 fluxes arise from gap-filling. Therefore, the random uncertainties for GEP, R_e, NEE, and CH_4 fluxes were calculated using different window sizes for gap-filling. The fixed moving-window method was used. For example, the fitted curve was determined by the data between 60 days into past and 60 days into future when the window size is 120 days. Window sizes of 30, 45, 60, 75, 90, 120, 150, 180, and 365 days were selected for GEP, R_e, and NEE. The same selections of window sizes with three additions (210, 240, and 270 days) were applied for estimating the uncertainties in the CH_4 budget. However, when the window size was too small, a fitted curve could not be obtained for some periods (e.g. not enough variability in controlling variables or occurrence of data gaps due to weather conditions and power limitations). Any gaps caused by using window sizes too small for modelling GEP, R_e, and CH_4 fluxes were filled by values obtained using the smallest window sizes that successfully produced a fitted curve. The smallest window sizes that successfully produced valid fitted curves for GEP, R_e, and the CH_4 budget were 85, 30, and 195 days, respectively.

The average vale and uncertainty of annual GEP, R_e, and NEE using all combinations of window sizes were 413 ± 16, 234 ± 10, and 179 ± 19 g C m^{-2} $year^{-1}$, respectively. The annual values of GEP, R_e, and NEE from the combinations (90 days for GEP and 120 days for R_e) chosen in the manuscript are close to the averages from all combinations. The average value and uncertainty from all different window sizes for annual CH_4 budget is 17 ± 1 g C m^{-2} $year^{-1}$. Therefore, we decided to use a window size of 365 days for CH_4 fluxes to cover the full range of soil temperatures in a single function.

We did not consider additional methods (e.g. neural network approaches) for gap-filling due to limitations in resources. We argue that the method of estimating uncertainties in annual flux measurements by using different gap-filling window sizes should suffice and gives a good idea of the seasonally changing responses to the controls.

2) The gap filling of CH4 is based on regression of the flux against soil temperature. I suggest, to consider to fit parameters of Eq. 3 in the window similar to Re and GEP, not for whole year. The different environmental condition (water table level, vegetation development, temperature of deeper soil levels ect.) can result in different respond of CH4 flux for temperature. The estimation of the parameters in the window would allow to include these influences.

[Response]

As mentioned in the response to comment 1, a time-dependent calculation of the response curve was additionally added, and the results are presented in the revised manuscript.

3) The global warming potential (GWP) is the most common measure to asses a com- bined impact of CH4 and CO2 emission on climate. However, it assumes a pulse emission which is not a case for wetlands, thus the applicability of GWP to asses the role of these ecosystems in the Earth's global radiation budget can be questioned (e.g. Neubauer and Megonigal, 2015; Petrescu et al., 2015). The author could refer to this problem in discussion.

[Response]

Thank you very much for this valuable suggestion. We agree and add the following statement at the end of Sec. 4.5 (L 324):

"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 CO_2 and CH_4 fluxes can not be evaluated) and alternative models were proposed (Frolking et al., 2007; Fuglestvedt et al., 2000; Neubauer and Megonigal, 2015; Petrescu et al., 2015; Smith & Wigley, 2000)."

SPECIFIC COMMENTS TO THE AUTHOR(S)

1) L 40 and in other places in text: "wetlands . . . sequester from -146 to -266 g CO2-C m-2 year-1" - negative sequestration means emission? It is easy to guess in this case, especially for those who are familiar with EC measurements, but in general it is not obvious, so one must be careful about a sings of the fluxes (for example nest in the text sequestration in GEP is positive). Please look through the text to clarify.

[Response]

Thank you very much for the suggestion. First, we removed the minus signs on L 40 as follows:

"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)."

Second, we clarified the sign convention and added the following explanation at the end of Sec. 3.3 (L 150):

"In this study, net fluxes of CO_2 and CH_4 toward the ecosystem surface are negative and net fluxes from the ecosystem surface to the stmosphere are positive. Therefore, negative NEE and F_m represent net CO_2 and CH_4 uptake, respectively."

2) L 265: "In June and July, the fitted curve stayed at 1 µmol m-2 s-1 because Ts,5cm remained above 15oC" – argumentation is not clear for me.

[Response]

Thank you very much for the suggestion. We rephrased the argumentation:

"In June and July, due to general warm condition (>15℃), R_e remained nearly constant at ~1 µmol m^{-2} s^{-1} (the fitted curve stayed in the plateau phase)."

3) L 271: "Two other controls on Re explored were air temperature (Ta) and WTH." Whereas role of WTH is already pointed above (L 268): "Another factor could be the WTH"

[Response]

Thank you very much for the suggestion. We modified the sentence as:

"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 $T_{s,5cm}$ when ..."

4) L 324-326: Last two sentences in the paragraph seem to be loosely related to the previous.

[Response]

Thank you very much for the suggestion. We decided to delete the last two sentences from L 324 to L 326 for clarity.

Referee #2

MAIN COMMENTS TO THE AUTHOR(S)

1) My greatest concern is that there is insufficient testing of the results via thorough reference to the wetland flux literature. Specifically, the CO2 flux component (NEE, GEP, Re) magnitudes are compared in detail with results from other types of ecosystems in the region that the authors are familiar with (Table 2), being forests and grassland, but not with relevant wetland studies.

[Response]

We agree with the comments from the referee and have added the following text on additional comparisons to wetland studies at the end of Section 4.3.1 (at line 254):

"The annual NEE in this study was more negative than in the majority of previously reported NEE values for pristine temperate peatlands, which were weak sinks, typically in the range of -50 g 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). Values that are comparable to the current restored wetland were reported in five pristine temperate wetlands: −248 g C m^{-2} year^{-1} (Lafleur et al., 2001), −234 g C m^{-2} year^{-1} (Campbell et al., 2014), -210 g C m^{-2} year^{-1} (Fortuniak et al., 2017), −189 g C m^{-2} year^{-1} (Flanagan and Syed, 2011), and −103 g C m^{-2} 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 CO_2 sources, with NEE ranging from +103 g C m^{-2} year^{-1} to +142 g C m^{-2} year^{-1} (Strack and Zuback, 2013; Richards and Craft, 2015; Järveoja et al., 2016). Other measurements in restored wetlands, however, were sinks, all of them stronger than in this study, with NEE values ranging from -804 g C m^{-2} year^{-1} to -270 g C m^{-2} year^{-1} (Hendriks et al., 2007; Badiou et al., 2011; Herbst et al., 2013; Knox et al., 2015; Anderson et al., 2016). 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 et al., 2002) and from an Atlantic blanket bog (Sottocornola and Kiely, 2010; McVeigh et al., 2014), both of which experienced a lower mean annual temperature."

2) There is a growing body of literature reporting annual and sub-annual FCH4 data from EC sites over wetlands, yet little reference to this literature is made.

[Response]

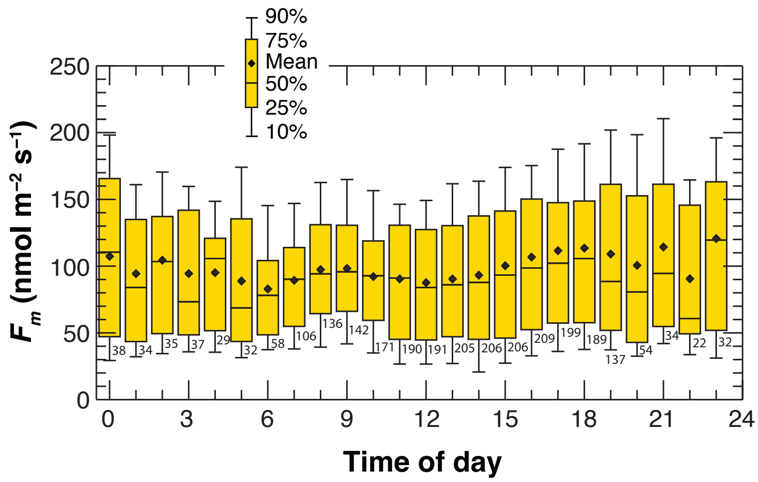
We appreciate reviewer's comments. In order to provide a more comprehensive comparison of our CH_4 fluxes, we added the following paragraph to Section 4.4.1 (it starts at line 298):

"The annual CH_4 flux in this study area was lower than CH_4 fluxes reported for other restored wetlands (Anderson et al., 2016; Hendriks et al., 2007; Knox et al., 2015; Nahlik & Mitsch, 2010). Despite the study area being flooded for most of the study year, CH_4 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 CH_4 flux from a restored wetland in Denmark that was lower than in this study (9 to 13 g CH_4-C m^{-2} $year^{-1}$). Our annual CH_4 flux at 16 g CH_4-C m^{-2} $year^{-1}$ was comparable to an average natural temperate wetland CH_4 flux, which is typically around 15 g CH_4-C m^{-2} $year^{-1}$ (Nicolini et al., 2013; Turetsky et al., 2014; Abdalla et al., 2016; Fortuniak et al., 2017). The CH_4 fluxes from a number of temperate and tropical pristine wetlands exceeded the CH_4 fluxes reported in this study, including emissions from marshes in the Southwestern US (130 g CH_4-C m^{-2} $year^{-1}$, Whiting & Chanton, 2001), tropical wetlands in Costa Rica (82 g CH_4-C m^{-2} $year^{-1}$, Nahlik & Mitsch, 2010), and marshes in the Midwestern US (50 g CH_4-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."

3) The authors may have made calculation errors in converting 30-minute fluxes through to annual values, certainly this appears to be the case for the methane fluxes shown in Fig. 6, and listed in Table 1.

[Response]

Thank you very much for bringing this to our attention. In Figure 6, we actually plotted only data that was measured (hence the different number of cases in each hour), and we excluded gap-filled data. There were significantly more datasets available from the summer half-year (higher CH_4 fluxes) than from the winter half-year (lower CH_4 fluxes), consequently the data in the figure cannot be simply averaged. To make this clearer, we have changed the caption and corrected the units (it was incorrectly labelled "µmol" instead of "nmol"). The corrected Fig. 6 is as follows:



The new caption reads:

"Figure 6: ~~(a)~~ Diurnal course of ~~filled~~ measured CH_4 fluxes from the EC-2 system during the study period."

Also, we have corrected the related text in Section 4.4.2 as follows:

"The ensemble diurnal courses of the ~~gap-filled~~ CH_4 fluxes ~~(measured CH_4 emissions and gap-filled by modelled CH_4 fluxes)~~ measured by the EC-2 system are shown in Fig. 6 from 16th June 2015 to 15th June 2016."

SPECIFIC COMMENTS TO THE AUTHOR(S)

1) Lines 38-40. Many of the cited studies here are horribly out of date or completely inappropriate. For instance, den Hartog et al. (1994) appears to be only an energy balance study and Schulze et al. (1999) is a forest study. Citing incorrectly at this early stage of a manuscript is a sure way for a reviewer to lose confidence!

[Response]

We appreciate reviewer's comments. The first paragraph of the introduction has been re-written to include more recent studies and omits den Hartog et al. (1994) and Schulze et al. (1999) as follows:

"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 they act as a major sink for the long-term C storage by sequestering carbon dioxide (CO_2) from the atmosphere. For example, strong C sinks (896 to 1139 g CO_2-C m^{-2} yr^{-1} and 1236 g CO_2-C m^{-2} $year^{-1}$) were found in Southeast USA and Eastern France, respectively (Mitsch et al. 2013; Grasset et al., 2016). Other wetlands around the world sequester around 100 g CO_2-C m^{-2} $year^{-1}$ (Petrescu et al., 2015; Bortolotti et al., 2016; Lu et al., 2016). 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). However, wetlands emit significant quantities of methane (CH_4), a powerful greenhouse gas (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 (Bergamaschi et al., 2007; Bloom et al., 2010; Ciais et al., 2013). 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). Their dynamics have played an important role in the global C cycle during the Holocene period (Gorham, 1991; Yu, 2011; Menviel and Joos, 2012), and it has been shown that it is crucial to include peatlands in the modelling and analysis of the global C cycle ~~to mitigate the changes in other C reservoirs is highly relevant~~ (Frolking et al., 2009; Wania et al., 2009; Kleinen et al., 2010)."

2) Line 40-41. Again, there seems little rationale for choosing these particular references as representative. Overall, I suggest that the introduction should contain as up-to-date references as possible, especially in the wetland eddy flux discipline where so many recent advances have been made.

[Response]

We appreciate reviewer's comments. The Introduction Section has been expanded by adding up-to-date citations (please see the previous response).

3) Line 46. Details of Mundava reference appears to be incorrect.

[Response]

We appreciate reviewer's correction. This reference has been discarded to avoid using a thesis as reference, and replaced by Roulet (2000) and Yu et al. (2010).

4) Lines 58-59. Poorly written text.

[Response]

We have now rephrased the text in reference to make it clear:

"Additionally, degraded peat increases the risk of peatland fires, which could consequently cause significant CO_2 emissions (Gaveau et al., 2014; Page et al., 2002; van der Werf et al., 2004)."

5) Lines 70-72. The three references supporting this statement about this "other study" appear to be a review followed by two papers describing studies from two different wetlands.

[Response]

Thank you very much for the suggestion. We have corrected the text as follows:

"In other studies, re-establishing the conditions…"

6) Lines 80-84. No mention of the role of DOC flux contributing to the overall net C flux. Exports of C via DOC can make up a major component. This should be acknowledged in the paper, and a justification made for why it was not assessed.

[Response]

We appreciate reviewer's comments. A mention of DOC and its role in net C flux has been made at the end of Section 4.3.1 (at line 254):

"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 g C m^{-2} $year^{-1}$ (Hendriks et al., 2007; Roulet et al., 2007; Waddington et al., 2008; Koehler et al., 2011), although, Chu et al. (2014) reported a net DOC import for a marsh of 23 ± 13 g C m^{-2} $year^{-1}$. D'Acunha et al. (2016) estimated DOC export for the current study area for Jan – Dec 2016 to be 22.4 g C m^{-2} $year^{-1}$ (15% of annual NEE)."

7) Section 2, Study area. It would be nice to have some more brief details of BB, such as area, mean annual climate statistics (see later comment).

[Response]

Thank you very much for the suggestion. We added the information at line 86 and line 101 as follows:

"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."

"… 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 ℃ and average annual precipitation was 1189 mm. Following rewetting, …"

8) "... highest emissions under a high water table"? Maybe "... associated with high water tables".

[Response]

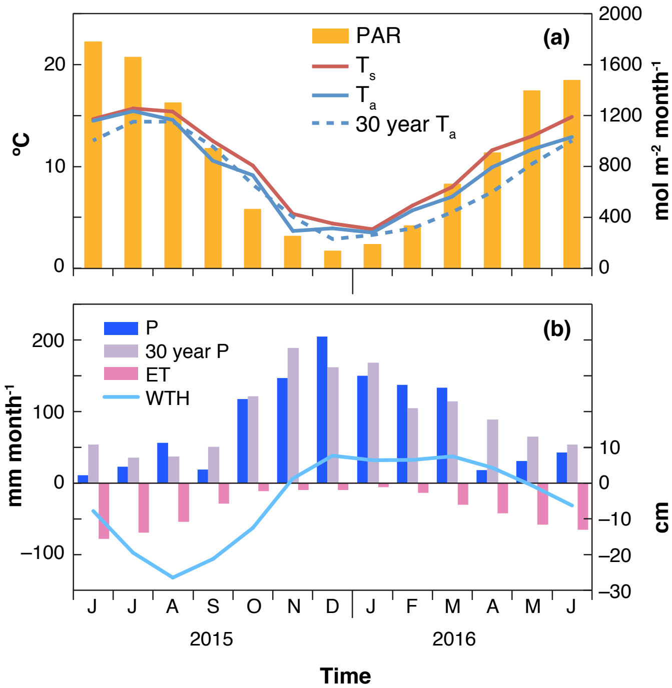
Thank you very much for the suggestion. The suggested correction has been made:

"… highest emissions associated with high water tables."

9) "... reduced ET as a consequence of senescence." Are there data on this? Reference to another study? Implies a definitive finding, which would be a worthwhile result on its own, but no EC water vapour flux data were presented in the manuscript.

[Response]

Yes. We have continuous ET data which were gap-filled using REddyProc (Max Planck Institute for Biogeochemistry). Monthly ET values have been added to the figure showing the annual course of weather variables:



To make it further clear, we have now added more details at line 104 as follows:

"In September and October, a water table rise due to the increase in precipitation and reduced evapotranspiration (ET) 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 and Jeglum, 2006)."

10) The detail that the CSAT3 samples at 60 Hz is unnecessary.

[Response]

We appreciate reviewer's suggestion. This information was edited as follows (at line 127):

"The CSAT-3 measured the longitudinal, transverse and vertical components of the wind vector and sonic temperature and output data at 10 Hz."

11) Lines 130-131. Please describe at least whether fluxes were calculated on-line by the dataloggers or during post-processing. It would be useful if the URL for the Crawford et al. report were provided in the reference list.

[Response]

We appreciate reviewer's suggestion. The fluxes were calculated in the post-processing, and this information has been added as follows:

"… were calculated in post-processing of 30-min data blocks following the procedures documented in Crawford et al. (2013)."

Also, the permanent link (http://hdl.handle.net/2429/45079) was added in the reference list.

12) Line 143. There is no Lee et al. (2016) reference provided, but there is a Lee (2016) MSc thesis. Generally, referring to a thesis should be avoided.

[Response]

We appreciate reviewer's suggestion. As suggested, reference to the Lee (2016) thesis has been removed:

"Gaps in the climate data (<1% of the year) were filled using measurements at nearby climate stations."

13) Line 152. Isn't GEP normally defined as gross ecosystem production (i.e. equivalent to GPP)?

[Response]

Yes, GEP usually stands for gross ecosystem production or productivity, which is equivalent to gross primary production (GPP). GEP can also stand for gross ecosystem photosynthesis which is equivalent to gross ecosystem productivity. In order to be consistent, we modified the definition in Section 3.3.1 (line 153) as follows:

"…and gross ecosystem productivity (GEP), i.e. $\mathrm{NEE} = R_e - \mathrm{GEP}$."

Also, the name of Section 4.3.4 was corrected to:

" 4.3.4 Gross ecosystem productivity"

14) Line 165. Range of annual Re: Table 1 lists an even larger value.

[Response]

Thank you very much for pointing out the discrepancy. The sensitivity test of window sizes on gap-filling was re-run on a more comprehensive scale based on comments from Referee #1, as a result of which this sentence has been modified as follows:

"However, the 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} $year^{-1}$."

15) Section 3.3.2. Gap filling FCH4. Methane fluxes in wetlands are often the result of a complex interplay of drivers, involving multiple transport pathways and balance between production and oxidation. Moreover, the controls on FCH4 can easily change seasonally and from year to year (Goodrich et al., 2015). I doubt that such a simplistic gap filling procedure as described here is sufficient. This is the reason that multipleparameter (e.g. Brown et al., 2014) and neural network (e.g. Goodrich et al., 2015) methods are more standard. Therefore, some more convincing details of FCH4 gap filling are required.

[Response]

We appreciate reviewer's suggestion. We have tested the effects of all other possible controls including WTH, θ_w, oxidation reduction potential, and T_a on CH_4 fluxes. There was no relationship between these variables and CH_4 fluxes. We were forced to use the relationship between T_s and CH_4 fluxes. The strongest relationship was an exponential one with an R^2 value of 0.66 (logarithmic, linear and polynomial relationships resulted in R^2 values of 0.46, 0.52 and 0.54, respectively).

16) Line 190, Eq. 4. Please define the m values for completeness.

[Response]

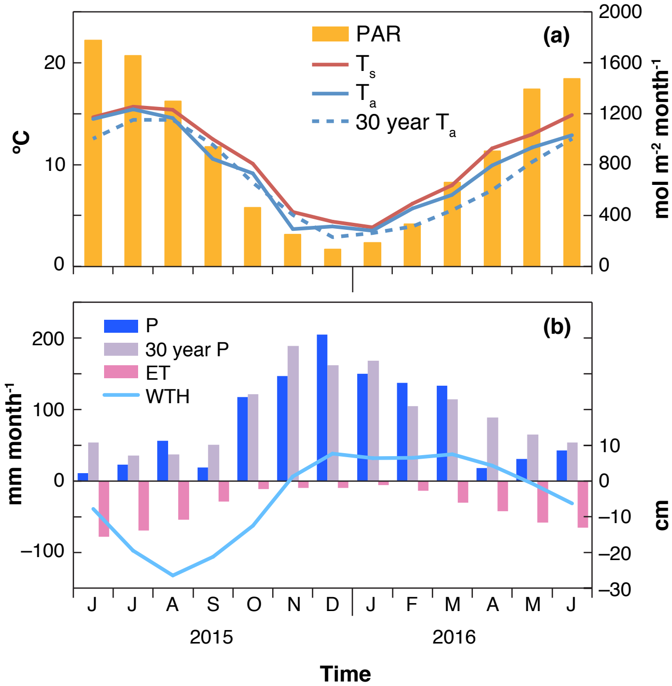
We appreciate reviewer's suggestion. The *m* values have been included:

"… , m_{CO_2} is the molecular mass of CO_2 (44.01 g mol^{-1}), and m_{CH_4} is the molecular mass of CH_4 (16.04 g mol^{-1})."

17) Section 4.1. Some comparison of seasonal and annual temperature and precipitation to long-term normals would be useful to justify how close to average (or not) the conditions during the study period were. Also (line 200), I don't believe one can justify listing annual precipitation totals to the precision of one decimal place, given the problems inherent in rain gauges!

[Response]

We appreciate reviewer's suggestion. First, we reduced the significant digits of annual precipitation totals to 0. Second, monthly precipitation and temperature measured during the study year at the tower and over 30 years at Vancouver International Airport were plotted in the figure showing the annual course of weather variables:



18) Line 210. Why list the author names (Kormann and Meixner) twice?

[Response]

We removed one of them and rewrote as follows:

"… using an analytical turbulent source area (turbulent footprint) model ~~from Kormann and Meixner~~ (Kormann and Meixner, 2001)

19) Line 217. What grasses? Were these wetland species?

[Response]

Yes, the common name of the dominant plant species (*Rhynchospora alba*) mentioned in Section 2 is white beak-sedge. The explanation has been added to Section 4.2.2 for clarity:

"Mosses and white beak sedge (the common name of *Rhynchospora alba*) started to grow …"

20) General comment: a figure showing the annual course of weather variables and water table would be very useful.

[Response]

We appreciate reviewer's suggestion. A new figure was made (see our response to Comment 9 above).

21) Lines 238-239. The "highest increasing rate of NEE" appears to be from March to April, not May.

[Response]

This sentence has been re-written as follows for clarity:

"The highest rate of increase in the magnitude of NEE and the highest magnitude of NEE both occurred early in growing season (Fig. 2)."

22) Line 242 onwards. It seems of very limited usefulness to compare the wetland fluxes to those from forests and grasslands, and it highlights the completely insufficient comparison with other wetland studies, both for restored peatlands and pristine or disturbed peatlands (see main comment above).

[Response]

We appreciate reviewer's suggestion. This comparison gives us information on how different the C exchange of a wetland is compared to other ecosystems in the same region, sharing the same climatic conditions. However, we have now added a detailed discussion comparing this study to other pristine and restored wetlands as follows. See our response to Comment 1 above.

23) Section 4.3.2. As it stands, Fig. 3 adds nothing to the paper other than a pretty picture. It would be of some use if there was a proper comparison made between these diurnal/seasonal patterns with the literature from other wetlands. FCO2 is only ever used in Fig. 3 and is not properly defined.

[Response]

We appreciate reviewer's comment. The label of scale (FCO_2) has been corrected to Fc for clarity. Figure 3 is the only place where detailed diurnal and seasonal trends in F_C are shown, which are valuable data and evidence to support our conclusions. To improve readability, we have now added the following information about Fig 3 (at line 256):

"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 in GEP changed with season resulting in the high magnitude of NEE during midday between May and July (~ -3.5 μmol m^{-2} 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 μmol m^{-2} s^{-1} for most of the study period. The rapid decrease in monthly R_e from May to June was caused by low R_e in early morning or at nightfall in June."

24) Section 4.3.3. Again, the magnitude of Re has not been adequately compared to other wetland flux literature, either on an instantaneous basis or seasonal/annual.

[Response]

We appreciate reviewer's suggestion. A detailed discussion comparing R_e from this study to other pristine and restored wetlands has been added at line 254 (see our response to Comment 1).

25) Line 277. I could not find where the measurement of theta_w (moisture content?) was described. Section 4.3.4. Again, this section on GEP is deficient in comparing their values for GEP and various timescales (and light response) with the relevant literature.

[Response]

We appreciate reviewer's suggestion. The information on the measurement of soil volumetric water content has been added to Section 3.1:

"A soil volumetric water content (θ_w) sensor (CS616, CSI) was inserted vertically to measure integrated θ_w from the surface to a depth of 0.30 m."

26) Lines 289-290. “We found out there was the light-independent photosynthesis ...”. This sentence is rather perplexing. How was this deduced? Also, the PAR range 300-500 is exactly in the range where GEP seems maximally dependent on light (Figs 5, S4)!

[Response]

We appreciate reviewer’s suggestion. The second paragraph in Section 4.3.4 was re-written for clarity as follows:

“Other possible controls on GEP explored were WTH and T_a. We found that WTH was not a control on GEP in the current study as the study area remained fairly wet throughout the year. Furthermore, the effects of T_a on GEP were approximately limited between 10 and 15 ℃.”

27) Section 4.4.2. Same comment as above about inadequate reference to relevant literature about CH4 fluxes. Lines 296-297. What do “weak” and “significant” mean in the context of CH4 fluxes when the literature is not referred to?

[Response]

We appreciate reviewer’s suggestion. We re-wrote the sentence at line 298 for clarity:

“Seasonally, it was a weaker CH_4 source in fall … .”

28) Line 305. Why was it surprising that there was not much of a diurnal course observed for FCH4? The authors seem to be completely unaware of why or why not this flux may or may not follow a diurnal course. Figure 6, with the whole annual period included, would almost certainly mask seasonal differences in diurnal patterns. Also, the units for FCH4 in Fig. 6 is surely incorrect. This should presumably be nmol m-2s-1.

[Response]

We appreciate reviewer's suggestion. In Figure 6, we actually plotted only data that were measured, i.e., gap-filled data were excluded (hence the different number of cases in each hour). There were significantly more data available from the summer half-year (higher CH_4 fluxes) than from the winter half-year (lower CH_4 fluxes). Therefore, we edited the text in Section 4.2.1 starting at line 307 to line 309 as follows:

"Surprisingly, there was only small diurnal variation observed for CH_4 fluxes in the summer months, as has been found in other studies (Juutinen et al., 2004; Wang and Han, 2005; Long et al., 2010; Sun et al. 2013). In the current study area, with changes in WTH and vegetation growth occurring during the year, there were likely several processes affecting CH_4 transport, which masked the diurnal pattern of CH_4 fluxes. Furthermore, $T_{s,5cm}$ appeared to be the main environmental control on CH_4 fluxes in this study but did not have as strong effect on CH_4 emissions as found in previous studies. Thus CH_4 was continuously emitted at a similar rate during daytime and nighttime. ~~Thermal effects such as recently reported by Poindexter et al., 2016 were not found.~~ From January to March and October to December, the winter half-year, 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 of soil temperature and may be partly due to convective turbulent mixing caused by cooling during the evening (Godwin et al., 2013)."

Thank you for pointing out the error in the units in Fig. 6. We have corrected the units to nmol.

29) Lines 305-306. "Thermal effects such as recently reported by ...". This is a bit too cryptic. Were the modelling methods of the Poindexter et al. (2016) followed, or is this just an attempt to justify the apparent lack of a diurnal pattern? Besides, at BB the water table was sometimes above the surface and sometimes below, and the annual vegetation growth changed (as described), so it is logical to assume that a variety of methane transport processes would have operated.

[Response]

We appreciate reviewer's suggestion. This reference was discarded for clarity, and the discussion of the diurnal course of CH_4 fluxes was added, please refer to our response to the previous comment.

30) Line 322. By CH4 emissions and CO2 uptake, I presume the CO2-eq values of these are being referred to.

[Response]

Thank you very much for the suggestion. We changed the text as follows:

"In short, the critical time period for both, CO_2 and CH_4 fluxes in terms of CO_2e, was the growing season when magnitude of fluxes changed differently across the growing season. "

31) Lines 328-330. This is by no means an adequate way to address the lack of comparison of the CO2 fluxes from this study with the peatland (or other wetland) literature.

[Response]

Thank you very much for the suggestion. A detailed discussion comparing this study to other pristine and restored wetlands has been added at line 254 (see our response to Comment 1).

32) Line 371. For peak's sake? Peat?

[Response]

This error has been corrected as follows:

"Chestnutt, C.: For peat's sake: A water …"

33) Figure 6. Units for FCH4 are surely incorrect. If these are actually nmol m-2s-1, a mean flux of around 100 nmol m-2s-1 should yield an annual flux of around 38 g CH4-C m-2yr-1, not the 16 g CH4-C m-2yr-1 as provided in Table 1. The authors should carefully check their flux conversion calculations, for both CH4 and CO2 fluxes, to provide some confidence it has been done correctly.

[Response]

Thank you very much for the suggestion. In Figure 6, we plotted only data that were measured (as we indicated in our response to Comment 28). There were significantly more data available from the summer half-year (higher CH_4 fluxes) than from the winter half-year (lower CH_4 fluxes), consequently the data in the figure cannot be simply averaged. We have changed the caption accordingly and corrected the unit (we incorrectly used "µmol" instead of "nmol"). The new caption reads:

"Figure 6: ~~(a)~~ Diurnal course of ~~filled~~ measured CH_4 fluxes from the EC-2 system during the study period."

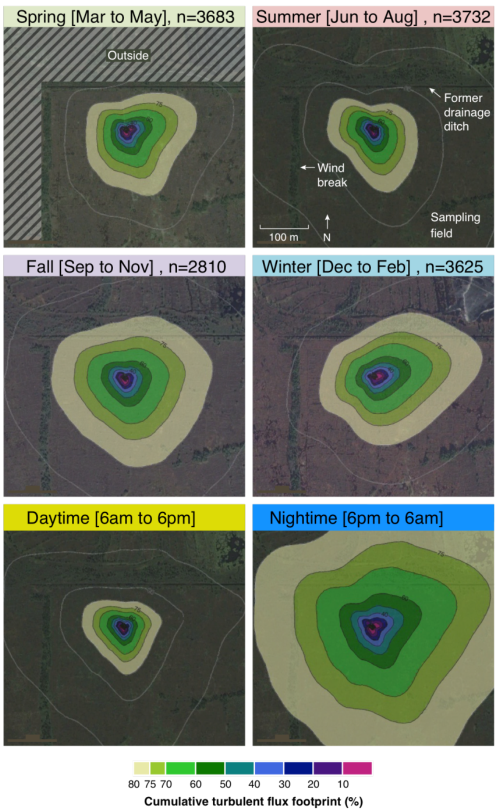
Also, we have corrected the related text in Section 4.4.2 as follows:

"The ensemble diurnal courses of the ~~gap-filled~~ CH_4 fluxes ~~(measured CH_4 emissions and gap-filled by modelled CH_4 fluxes)~~ measured by the EC-2 system are shown in Fig. 6 from 16th June 2015 to 15th June 2016."

34) Figure S1. North orientation should be indicated. Also, note that not all panels show max. contour of 90%.

[Response]

Thank you very much for the suggestion. The fact that not all panels show the 90% contour line is intentional. All source areas were calculated as gridded data for a 1 x 1 km box (open source code see https://github.com/achristen/Gridded-Turbulent-Source-Area). If a contour line for a certain probability reaches the border of the model domain, the exact shape of the probabilities outside the domain are unknown, and hence the contour cannot be drawn, even within the domain. The new figure was drawn for including north orientation and vegetation conditions in different seasons:



35) Figure S3. "Re curves" is not an adequate description. What does it mean "on first day of every two months"? This is not correct.

[Response]

Thank you very much for the suggestion. The new caption for Fig. S3 reads:

"Boxplots of measured R_e (nighttime NEE) plotted against $T_{s,5cm}$ with a fitted curve on the first day of each time period using a window size of 120 days."

36) Figure S4. Same comment about inadequate caption.

[Response]

Thank you very much for the suggestion. The new caption for Fig. S4 reads:

"Light response curves on the first day of each time period using a window size of 90 days."