



The effect of atmospheric turbulence and chamber deployment period on autochamber CO₂ and CH₄ flux measurements in an ombrotrophic peatland

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Abstract. Accurate quantification of soil-atmosphere gas exchange is essential for understanding the magnitude and controls of greenhouse gas emissions. We used an automatic, closed, dynamic chamber system to measure the fluxes of CO₂ and CH₄ for several years at the ombrotrophic Mer Bleue peatland near Ottawa, Canada and found that atmospheric turbulence and chamber deployment period had a considerable influence on the observed flux rates. With a short deployment period of 2.5 min, CH₄ flux exhibited strong diel patterns and both CH₄ and nighttime CO₂ effluxes were highly and negatively correlated with ambient friction velocity as were the CO₂ concentration gradients in the top 20 cm of peat. This suggests winds were flushing the very porous and relatively dry near-surface peat layers and reducing the belowground gas concentration gradient, which then led to flux underestimations owing to a decrease in turbulence inside the headspace during chamber deployment compared to the ambient windy conditions. We found a 9 to 57 % underestimate of the net biological CH₄ flux at any time of day and a 13 to 21 % underestimate of nighttime CO₂ effluxes in highly turbulent conditions. Conversely, there was evidence of an overestimation of ~100 % of net biological CH₄ and nighttime CO₂ fluxes in calm atmospheric condi-

tions possibly due to enhanced near-surface gas concentration gradient by mixing of chamber headspace air by fans. These problems were resolved by extending the deployment period to 30 min. After 13 min of chamber closure, the flux rate of CH₄ and nighttime CO₂ became constant and were not affected by turbulence thereafter, yielding a reliable estimate of the net biological fluxes. The measurement biases we observed likely exist to some extent in all chamber flux measurements made on porous and aerated substrate, such as peatlands, organic soils in tundra and forests, and snow-covered surfaces, but would be difficult to detect unless high frequency, semi-continuous observations were made.

1 Introduction

Northern peatlands in the boreal and subarctic regions play an important role in the global carbon cycle. They store a total of 270 to 547 Pg of carbon (C) as peat (Turunen et al., 2002; Yu et al., 2010), which is equivalent to 18–25 % of the C held globally in the top 1 m of soil (Jobbágy and Jackson, 2000), though these estimates are considered low when the peatlands containing permafrost and at higher latitudes

are included (McGuire et al., 2009; Tarnocai et al., 2009). While northern peatlands have been net sinks of C for millennia, natural and anthropogenic disturbances could lead to substantial release of C to the atmosphere (Turetsky et al., 2002). The land-atmosphere exchange of carbon dioxide (CO₂) and methane (CH₄) gases largely governs the overall peatland carbon balance (Roulet et al., 2007) as well as the net radiative forcing impacts of peatlands over time (Frolking et al., 2006). Accurate measurement of land-atmosphere gas fluxes is needed to quantify peatland gas exchange at different spatial-temporal scales, understand the environmental controls on gas fluxes, and parameterize peatland and global carbon models (Limpens et al., 2008).

Flux measurement in peatlands is often done using chamber enclosures and/or micrometeorological methods, e.g. eddy covariance. Eddy covariance gives continuous, spatially-averaged gas fluxes over an ecosystem at scales of 10⁴–10⁵ m² (Scanlon and Kiely, 2003), but it does not provide any mechanistic detail about the flux components at a finer spatial scale (Griffis et al., 2000). In contrast, chamber methods measure gas concentration changes in a headspace resulting from small, well-defined areas (0.01–10 m²). Most studies on small-scale peatland C dynamics have employed manual chambers (e.g. Carroll and Crill, 1997; Moore et al., 2002; Pelletier et al., 2007), which are relatively easy and inexpensive to use, but difficult to sample more frequently than weekly because of labour constraints. Automated chambers thus far have not been used extensively for flux measurements owing to the high cost and infrastructure requirements for installation and operation (Savage and Davidson, 2003), yet they offer great opportunity to collect flux data with a much higher temporal resolution than manual chambers.

The use of chamber enclosures is known to create some artefacts and bias in flux measurements. One artefact associated with the deployment of closed chambers is the accumulation of gases in the chamber headspace and the subsequent decrease in diffusive concentration gradient and measured flux over time (Davidson et al., 2002). This suggests that chamber deployment period should be kept short to minimize the build-up of gases inside the chamber. On the other hand, a short chamber deployment period increases the uncertainty of flux calculation and the difficulty in obtaining a detectable flux (Khalil et al., 1998). There are also potential errors in flux measurement at the beginning of deployment period, since chamber placement on the soil surface can cause a disturbance of the atmospheric interfacial layer (Hutchinson et al., 2000). The duration and timing of chamber deployment is therefore important to obtaining accurate flux estimates.

Atmospheric turbulence has been shown to exert considerable influence on gas transport in soils (Kimball and Lemon, 1971). Numerous studies have observed the effects of atmospheric turbulence on gas dynamics in soil pore space in grassland (Flechard et al., 2007), pine forest (Maier et al., 2010) and black spruce boreal forest (Hirsch et al.,

2004). Moreover, highly turbulent atmospheric conditions were found to enhance soil gas fluxes measured by both open chambers in a spruce forest (Subke et al., 2003) and closed chambers in an aggrading deciduous forest (Bain et al., 2005), while Schneider et al. (2009) observed an overestimation of nighttime respiration under calm conditions in a boreal peatland by closed chambers. Atmospheric turbulence has a more pronounced effect on gas exchange from soils with large pore size and low moisture content owing to significantly greater air permeability (Kimball and Lemon, 1971; Conen and Smith, 1998). In light of these findings, there is a need to better understand how headspace gas concentration is affected by turbulence and pressure disturbances arising from chamber deployment (Kutzbach et al., 2007). Autochambers have the advantage of providing a large empirical data set covering a range of turbulence conditions that occur naturally in the field for statistically robust analysis.

The exchange of CO₂ and CH₄ at the Mer Bleue bog, a peatland with very porous and aerated peat, was measured using a closed dynamic autochamber system with a short deployment period of 2.5 min. We found strong diel variations in CH₄ flux with significantly larger nighttime emissions. Diel patterns in CH₄ flux are not as clearly prescribed as those of CO₂ that typically show net uptake during the day and emissions at night on vegetated terrain (e.g. Cai et al., 2010). Recent studies using the eddy covariance technique, a method which is not subject to chamber-specific artefacts, have reported very different diel CH₄ flux patterns in peatlands. Higher CH₄ flux during the daytime was observed in a boreal tree fen (Long et al., 2010) as well as a Dutch peat meadow (Hendriks et al., 2010), attributable to greater temperature and vapour pressure gradients that enhanced both plant-mediated convective flow as well as transpiration loss of dissolved CH₄ in soil water. On the other hand, Baldocchi et al. (2012) reported higher CH₄ emissions at night in a peatland pasture, owing to collapse of the nocturnal boundary layer and elongation of flux footprint to elevated CH₄ source areas in calm conditions. In a subarctic peatland dominated by tall graminoids, no diel cycle in CH₄ flux was seen throughout the year (Jackowicz-Korczycki et al., 2010). Some studies that used autochambers on wetlands have reported CH₄ or total hydrocarbon fluxes for time periods of a day or more (Mastepanov et al., 2008; Bäckstrand et al., 2010), making it hard to deduce the variability over shorter time periods from their results. Our central research question is whether the observed diel CH₄ flux pattern at Mer Bleue is a result of natural processes or measurement artefacts. If it is the former, then biological and biogeochemical reasons for the repetitive pattern of variability need to be studied to provide an explanation. If the latter, modifications to the chamber methodology may be needed to eliminate or at least greatly reduce the measurement artefacts.

We hypothesize that the observed diel variability of CH₄ flux at the Mer Bleue bog is largely governed by physical processes associated with artificial and abrupt

changes of atmospheric turbulence by chamber deployment. Turbulence-driven pressure fluctuations can induce mass flow of gas from soil pore space to the atmosphere, reducing gas concentration and storage in soils (Maier et al., 2010). We expect that, during daytime when turbulent conditions are dominant, the reduction in diffusive concentration gradient in surface peat before chamber lid closure will lead to a lower transient CH₄ flux measured by autochambers when the deployment period is short. The abrupt decrease in headspace turbulence following chamber deployment will cause an increase in gas storage in the peat pore space until sufficient time is given for the concentration gradient to adjust to the new transport resistances. For the same reason, nighttime CO₂ efflux will be lower when measured in highly turbulent conditions. In calm conditions, mechanical mixing of headspace air by fans can increase the near-surface concentration gradient and lead to an immediate enhancement of gas fluxes following chamber deployment (Hutchinson et al., 2000). For example, Schneider et al. (2009) observed non-linear increases in headspace CO₂ concentration when the closed manual chamber was deployed during calm nights at three microsites of a boreal peatland. We hypothesize that, in the calm conditions that occur during some nights, chamber-induced turbulence enhances both soil CO₂ and CH₄ effluxes measured during the initial period after autochamber closure, before an equilibrium is reached between the net rates of gas production in peat and gas exchange across the peat surface.

The objectives of our study are to (1) investigate the relationship between atmospheric turbulence and autochamber CH₄ and nighttime CO₂ fluxes, (2) examine the influence of atmospheric turbulence on the surface peat CO₂ concentration gradient, and (3) determine the effects of chamber deployment period on gas fluxes measured by autochambers.

2 Methods

2.1 Site description

Mer Bleue peatland is a 28 km² ombrotrophic bog located near Ottawa, Canada (45.41° N, 75.52° W). This region has a cool continental climate, with a mean annual temperature of 6.0 ± 0.8 °C and mean annual precipitation of 943.5 mm (1971–2000 climate normals) (Environment Canada, 2011). Field measurements were made at a dome-shaped bog in the northwest part of this peatland. Peat depth reaches about 5 to 6 m near the centre of the bog, and is shallower (< 0.3 m) near the beaver pond margin (Roulet et al., 2007). The surface of this peatland is completely covered by *Sphagnum* moss (*Sphagnum magellanicum* Brid., *Sphagnum capillifolium* (Ehrh.) Hedw., *Sphagnum angustifolium* (C.E.O. Jensen ex Russow) C.E.O. Jensen, *Sphagnum fallx* (Klinggr.) Klinggr.), and the vascular plant cover is dominated by low growing ericaceous evergreen shrubs (*Chamaedaphne calyculata* (L.) Moench, *Ledum groen-*

landicum Oeder, *Kalmia angustifolia* L.), with an occasional mix of deciduous shrubs (*Vaccinium myrtilloides* Michx.), sedge (*Eriophorum vaginatum* L.) and forb (*Maianthemum trifolium* (L.) Sloboda).

This bog is relatively dry, with a mean growing season (May to October) water table depth of 42.7 cm from the top of hummock over 1998–2008 (Teklemariam et al., 2010). It has a hummock-lawn-hollow microtopography, with a mean difference of 17 cm in elevation between the hummock and hollow surfaces (Wilson, 2012). Depending on the microtopographic location, the top 10–30 cm peat at Mer Bleue is fibric and has a total porosity and macroporosity of greater than 0.9 and 0.8, respectively (Dimitrov et al., 2010). Air-filled porosity of surface peat in the unsaturated zone of this bog is between 0.82 and 0.92 (Deppe et al., 2010).

2.2 Autochamber system

We set up 10 autochambers at the Mer Bleue bog within a 15-m radius about 50 m south of the eddy covariance tower. Chamber locations were chosen to represent the major plant communities, while covering a range of water table and leaf area (Table 1). Wooden boardwalks were constructed to minimize disturbance during access to the chambers. The dynamic, closed autochamber system established at this bog was identical to the one used in a moderately rich treed fen (Cai et al., 2010), a temperate Douglas-fir forest (Drewitt et al., 2002), a boreal aspen forest (Griffis et al., 2004) and two boreal black spruce forests (Gaumont-Guay et al., 2008; Bergeron et al., 2009). The autochamber consisted of a transparent Plexiglas[®] dome fitted to a PVC cylinder with a hinged aluminum frame. The near semi-spherical dome had a height of 20.5 cm, and the PVC cylinder had an internal diameter of 52 cm, a thickness of 1 cm and a height of 38.5 cm. Hence, each autochamber covered a surface area of 0.21 m². The PVC cylinders were inserted 16 to 31 cm deep into the peat, leaving about 7 to 22 cm above the peat surface, but below the height of the top of the shrubs. After insertion, any gaps between the outside of the cylinder and surrounding peat were filled with surface peat taken from elsewhere at the site. A partially inflated bicycle tube sealed to the top of the cylinder and a foam gasket on the aluminum flange at the dome base ensured a good seal when the chamber was closed. A small brushless fan within the dome mixed the air in the chamber headspace, and a coiled 50-cm-long open-ended vent tube on the dome top ensured equilibration of pressure between the inside and outside of chamber during flux measurements.

Control of the autochamber system, including chamber selection, measurement timing and data acquisition, was controlled by a datalogger (CR23X, Campbell Scientific, UT, USA). A pneumatic cylinder assembly (Model BFT-173-DB, Bimba Manufacturing, IL, USA) connected to an oil-free air compressor (Model CPFAC2600P, Porter Cable, TN, USA) opened and closed the chamber dome. Sampling tubes

Table 1. Vascular plant species, mean water table depth (maximum and minimum depths in parentheses) and peak vascular green area index (VGA) for the 10 autochambers.

Chamber number	Vascular plant species ^a	Water table depth (cm)		VGA (m ² m ⁻²)
		2009 ^b	2010 ^c	
Sedge-dominated				
1	Ev, Vm, Lg, Ka	-24.8 (-36.3, -16.3)	-25.5 (-48.9, -13.7)	0.82
2	Ev, Cc, Lg, Vm, Ka	-29.5 (-45.3, -18.4)	-31.4 (-57.3, -18.7)	1.08
4	Ev, Lg, Cc, Ka	-18.7 (-29.2, -7.5)	-21.0 (-48.9, -7.3)	1.35
7	Ev, Cc, Mt, Lg	-19.1 (-32.8, -9.4)	-21.9 (-45.2, -8.2)	1.13
Shrub-dominated hollow				
8	Mt, Lg	-19.4 (-34.6, -8.8)	-18.9 (-44.1, -3.9)	2.09
10	Mt, Lg	-19.9 (-33.6, -9.6)	-22.2 (-45.9, -7.9)	2.00
Shrub-dominated lawn				
3	Cc, Vm, Mt, Lg	-29.2 (-41.9, -19.0)	-30.1 (-54.3, -14.5)	1.52
9	Lg, Mt, Ka	-24.0 (-36.4, -15.4)	-26.6 (-48.3, -12.7)	0.47
Shrub-dominated hummock				
5	Cc, Lg, Vm	-35.3 (-47.1, -24.8)	-37.0 (-63.1, -24.1)	1.12
6	Cc, Vm	-37.2 (-49.1, -26.0)	-38.0 (-61.8, -26.3)	1.56

Cc: *Chamaedaphne calyculata*, Ev: *Eriophorum vaginatum*, Ka: *Kalmia angustifolia*, Lg: *Ledum groenlandicum*, Mt: *Maianthemum trifolium*, Vm: *Vaccinium myrtilloides*.

^a In descending order of peak VGA. Only species with peak VGA > 0.1 m² m⁻² are included.

^b From DOY 142 to 341.

^c From DOY 85 to 339.

(Synflex 1300, 4.3 mm i.d., Saint-Gobain Performance Plastics, NJ, USA) connected to the gas inlet and outlet located at the top of chamber dome led to a sampling manifold controlled by solenoid valves (Model DDBA-1BA, MAC Valves, MI, USA). Concentrations of CO₂ and CH₄ were measured by a closed-path infrared gas analyzer (LI-6262, LI-COR, NE, USA) and a fast methane analyzer based on off-axis integrated cavity output spectroscopy (DLT-100, Los Gatos Research, CA, USA), respectively. The LI-6262 was manually calibrated weekly using ultra-high purity nitrogen gas containing no CO₂ (for zero) and 356 μmol mol⁻¹ of CO₂ (for span), and the fast methane analyzer was calibrated with CH₄ standard gas (1.8 and 5.01 μmol mol⁻¹) once at the beginning of measurement season. Air was circulated to the LI-6262 and back to the chambers at a flow rate of 3.51 min⁻¹ by an AC linear pump (Model DDL, Gast Manufacturing, MI, USA). The internal pump on the fast methane analyzer sub-sampled the air stream at approximately 0.5 l min⁻¹. The datalogger, pump, and gas analyzers were all placed inside temperature-controlled housings.

The autochamber system was in operation between 22 May and 7 December in 2009 and between 26 March and 5 December in 2010. Prior to 6 July 2010, the autochambers were programmed to close sequentially to measure gas fluxes for 2.5 min to provide one measured flux for each chamber every 30 min. Fluxes were continuously measured between 02:00 and 24:00 EST daily. Between midnight and 02:00,

the system was used to estimate the effective volume of the chamber (Drewitt et al., 2002). From 6 July 2010 onwards, the chamber deployment period was increased from 2.5 to 15 min, and one flux measurement was made for each chamber every three hours. To investigate the effect of chamber deployment period on measured fluxes, we operated only two autochambers using extended deployment periods of 15 min for three days (23–26 June) and 30 min for four days (26–30 June 2010). Analog outputs from the gas analyzers were sampled at 1 Hz by the datalogger, averaged every 5 s, and downloaded automatically to a PC located in a hut on site. All high frequency data were retained for flux processing.

2.3 CO₂ concentration profile system

A profile system was set up within 25 m of the autochambers to monitor CO₂ and water vapour concentrations in the air at seven different levels, namely 255, 120, 20 and 10 cm above the peat surface, in the *Chamaedaphne* canopy (5 cm above peat surface), and on the *Sphagnum* peat surface of both a hummock and hollow (5 and 25 cm below the *Chamaedaphne* canopy respectively). Air samples were drawn through sampling tubes (Synflex 1300, 4.3 mm i.d. and Bev-A-Line IV, 3.2 mm i.d.) into an infrared gas analyzer (LI-6262, LI-COR, NE, USA) by an AC linear pump (Model SPP-15EBS-101, Gast Manufacturing, MI, USA). The seven different levels were sampled

sequentially for two minutes each using solenoid valves (Model 701N13A5P, Honeywell, CT, USA), with air being flushed through the system in the first minute and CO₂ and water vapour concentrations measured every two seconds and then averaged in the second minute. Operation of this system was controlled by a datalogger (CR10X, Campbell Scientific, UT, USA).

We also measured CO₂ concentrations in the peat profile by non-dispersive infrared CO₂ sensors (Model CAR-BOCAP GMM220, Vaisala, Finland) that were enclosed by an expanded polytetrafluoroethylene (PTFE) membrane permeable to gas but not water. A few meters away from the air profile system, we cut out peat blocks, and inserted the sensors horizontally in the pit face at 5, 10, 20 and 40 cm depth at a hummock, and 5 and 10 cm depth at a hollow. The sensors were installed a few years before the actual measurements made in 2009 to minimize any possible disturbance effects. Thermocouples were also installed next to the sensors to monitor peat temperature. The peat blocks were carefully returned to the pits. Peat pore space CO₂ concentration and temperature were measured at 5-min intervals and averaged every half hour on a datalogger (CR21X, Campbell Scientific, UT, USA).

2.4 Ancillary field measurements

We installed thermocouples into the peat at 10 cm depth inside each of the chamber cylinders to monitor peat temperature at 1 Hz for the calculation of half-hourly averages. Continuous 30-min records of water table position were obtained with a capacitance water level probe (Model Odyssey, Dataflow Systems, New Zealand) placed inside a perforated ABS tube (3.8 cm i.d.) in the peat besides each chamber. A perforated PVC tube (1.25 cm i.d.) was installed next to each ABS tube to manually measure water table position at weekly intervals in order to calibrate the capacitance probe records.

Friction velocity (u_*) was computed every 30 min as

$$u_* = \left[\left(\overline{u'w'} \right)^2 + \left(\overline{v'w'} \right)^2 \right]^{1/4} \quad (1)$$

from 20 Hz measurements of wind velocity measured in three dimensions (u , v , and w) with a sonic anemometer (Model R3-50, Gill Instruments, UK) prior to rotation to a natural wind coordinate system (Foken, 2008). Friction velocity is related to shear stress, the rate of transfer of momentum, and it varies with wind speed and stability for a given surface roughness (Oke, 1987). As part of the eddy covariance system for determining peatland CO₂ exchange, the sonic anemometer was mounted on an instrument tower at a height of 3 m and was also used to compute cup wind speed. Above the canopy, u_* does not change with height within the constant flux layer of the atmosphere (Oke, 1987). Within the 30 cm shrub canopy, we did not directly assess wind speed but, using the CO₂ concentration profile results in the text, we

showed that in highly turbulent conditions, gusts appeared to penetrate the canopy and into the near-surface peat. In addition, we measured air temperature (Model HMP35CF, Campbell Scientific Inc., UT, USA) 2 m above the surface, incoming photosynthetically active radiation (PAR, Model LI-190SA, LI-COR, NE, USA), and barometric pressure (Model CS105, Campbell Scientific Inc., UT, USA) at the site every 5 s and averaged them half-hourly (Lafleur et al., 2003).

2.5 Data analysis

Mole fractions of CO₂ and CH₄ measured in the autochamber headspace were converted to mixing ratios using the concurrent LI-6262 measurement of water vapour concentration to account for water vapour dilution effects. Methane flux ($\mu\text{mol CH}_4 \text{ m}^{-2} \text{ h}^{-1}$) and nighttime CO₂ efflux ($\text{mmol CO}_2 \text{ m}^{-2} \text{ h}^{-1}$) were then calculated from

$$F_{\text{gas}} = PV S / RT A \quad (2)$$

where F_{gas} is gas flux, P is barometric pressure (Pa), V is chamber geometric volume (m^3), S is rate of change in headspace gas concentration (expressed as $\mu\text{mol mol}^{-1} \text{ h}^{-1}$ for CH₄ and $\text{mmol mol}^{-1} \text{ h}^{-1}$ for CO₂), R is universal gas constant ($8.3144 \text{ Pa m}^3 \text{ mol}^{-1} \text{ K}^{-1}$), T is air temperature (K), and A is surface area of autochamber (m^2). S is determined by linear regression of gas concentration in chamber headspace against time over a period of 1.5 min, after discarding the data in the initial 45 s following chamber closure. Fluxes were accepted only if $r^2 > 0.9$ ($p < 0.01$, $N = 19$), except when CH₄ flux measured with a 15-min deployment period was $\leq 39 \mu\text{mol m}^{-2} \text{ h}^{-1}$. Then, a r^2 threshold of 0.7 was used due to both lower flux magnitude and sensitivity of analyzer signal output. The use of r^2 as a filtering criterion might underestimate the contribution of near-zero fluxes, yet the number of near-zero fluxes ($\pm 0.36 \text{ mmol CO}_2 \text{ m}^{-2} \text{ h}^{-1}$ and $\pm 26 \mu\text{mol CH}_4 \text{ m}^{-2} \text{ h}^{-1}$) removed due to low r^2 was small ($< 5\%$ of the whole data set for most chambers). Moreover, the u_* levels at which these rejected fluxes were measured had a similar distribution as for all the half-hourly u_* measured at the Mer Bleue site over a full year, indicating that the rejection of these small number of near-zero fluxes did not bias the analysis towards certain turbulence conditions. Poor quality flux data obtained during periods of equipment failure (e.g. broken tubing) and system maintenance were also removed from analysis. The poor quality fluxes could not be filtered out satisfactorily using a root-mean-square error (RMSE) threshold, since these fluxes were mostly collected when there were issues with leakage or broken tubing, and typically had a small magnitude as well as a small RMSE. All these quality control procedures led to the removal of 3 to 17% of all CO₂ fluxes and 2 to 28% of all CH₄ fluxes collected for a given chamber. Nighttime CO₂ respiration was calculated only when the half-hour PAR value was zero.

We also accounted for the water dilution effects in the air profile CO_2 concentration data and expressed these as $\mu\text{mol CO}_2 \text{ mol}^{-1}$ dry air. CO_2 concentrations measured by sensors in the peat profile were adjusted for temperature and pressure (Vaisala, 2011). Half-hour CO_2 concentration gradient in the top 20 cm surface peat of hummock was then estimated as the slope of the linear regression between pore space CO_2 concentration (measured at 0, 5, 10 and 20 cm below peat surface) and peat depth. Pearson correlation analyses were conducted to establish relationships between gas fluxes, concentration gradient, and environmental variables. All the data filtering and statistical analyses were conducted in MATLAB R2009a (MathWorks, MA, USA).

3 Results

3.1 Atmospheric turbulence and autochamber gas fluxes

Figure 1 shows the diel variability of monthly mean CH_4 flux as measured using a 2.5 min deployment period in 2009 from three autochambers located at a sedge-dominated hollow, a shrub-dominated hollow, and a shrub-dominated hummock. These three chambers represented the range of the microtopography and plant communities commonly found in the Mer Bleue peatland. A distinct diel CH_4 flux pattern was observed throughout the year for all chambers, with lower emissions during the day than at night. The difference in minimum daytime and maximum nighttime CH_4 flux (see Fig. 1) was greatest in the mid to late growing season between July and September. For instance, the difference was $703 \mu\text{mol m}^{-2} \text{ h}^{-1}$ at the sedge-dominated hollow in August but only $232 \mu\text{mol m}^{-2} \text{ h}^{-1}$ in November. Among the various collar locations, the diel variation in CH_4 flux was smallest at the shrub-dominated hollow. For example, mean CH_4 flux in September decreased from a nighttime maximum to a daytime minimum by 41.1 % at the shrub hollow, compared to 55.3 % and 74.6 % at the sedge hollow and shrub hummock, respectively (Fig. 1).

Time series plot of half-hourly CH_4 flux and u_* , which characterizes the strength of atmospheric turbulence, shows that the two variables were tightly and inversely related (Fig. 2). CH_4 fluxes were higher at night for most of the days over this two-week period when u_* was low. However, on DOY 206 when u_* increased throughout the 24-h period without dropping at night, CH_4 flux decreased consistently over the same period without exhibiting the usual diel CH_4 flux pattern. It is also interesting to note that the response of one variable to the change in the other was very quick. For instance on DOY 204, a sharp drop in u_* in the middle of the day was followed by an immediate increase in CH_4 flux rate measured by the autochamber in the same half hour.

We further investigated the relationship between u_* and autochamber CH_4 flux by correlation analysis using the half-

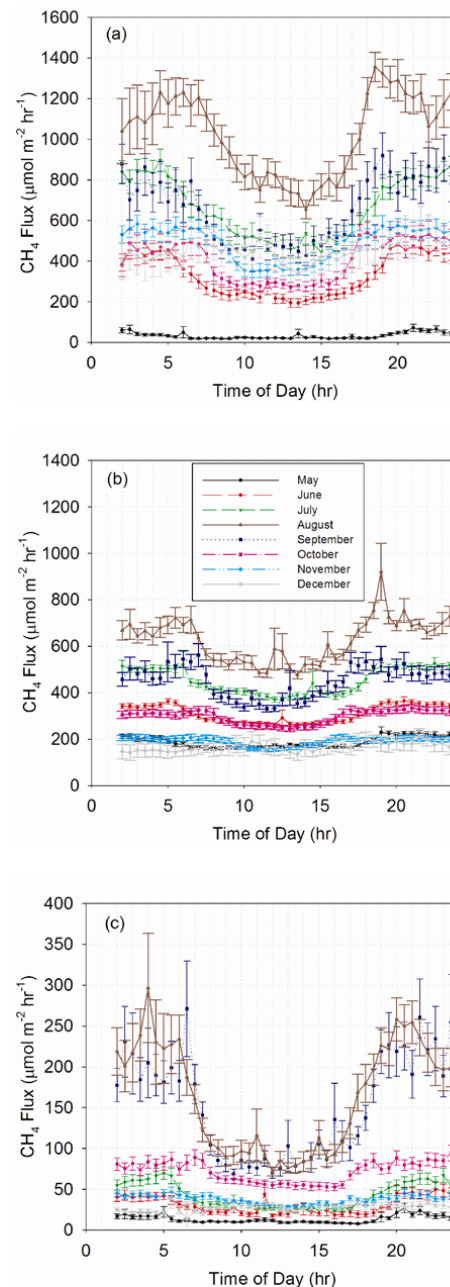


Fig. 1. Diel variability of monthly mean autochamber CH_4 flux from (a) sedge-dominated hollow, (b) shrub-dominated hollow, and (c) shrub-dominated hummock in 2009. Error bar indicates ± 1 standard error.

hourly data collected between June and September 2009. The data set was first stratified by air temperature in 5°C classes to control for the effects of temperature on flux rate. Table 2 shows that CH_4 fluxes from all the autochambers were significantly and negatively correlated with u_* when air temperature was between 5 and 25°C , while some of the autochambers did not have significant correlations for the 0 – 5°C and 25 – 30°C classes with smaller

Table 2. Correlation coefficients (r) between friction velocity and autochamber CH₄ flux stratified by air temperature in 5 °C classes from June to September 2009^a.

Chamber	0–5 °C		5–10 °C		10–15 °C		15–20 °C		20–25 °C		25–30 °C	
	r	N	r	N	r	N	r	N	r	N	r	N
Sedge-dominated												
1	–0.20*	135	–0.41**	373	–0.45**	836	–0.46**	1326	–0.48**	1033	–0.22**	275
2	NS	129	–0.23**	341	–0.23**	756	–0.25**	1112	–0.37**	878	–0.18**	242
4	NS	133	–0.28**	352	–0.18**	768	–0.24**	1142	–0.28**	898	NS	241
7	–0.36**	119	–0.51**	313	–0.50**	769	–0.55**	1261	–0.49**	994	–0.34**	268
Shrub-dominated hollow												
8	–0.32**	137	–0.52**	381	–0.28**	837	–0.29**	1329	–0.24**	1037	NS	276
10	–0.34**	139	–0.47**	379	–0.38**	833	–0.30**	1330	–0.35**	1031	–0.20**	275
Shrub-dominated lawn												
3	–0.22**	137	–0.39**	378	–0.16**	828	–0.20**	1314	–0.35**	1027	NS	271
9	–0.26**	101	–0.41**	325	–0.11**	741	–0.16**	1193	–0.21**	940	–0.23**	270
Shrub-dominated hummock												
5	NS	130	–0.23**	278	–0.14**	625	–0.21**	1027	–0.36**	905	NS	260
6	–0.22**	137	–0.30**	376	–0.21**	828	–0.25**	1321	–0.29**	1023	–0.26**	276

^a r = correlation coefficient; N = sample size; NS = not significant.

* Significant at the 0.05 level.

** Significant at the 0.01 level.

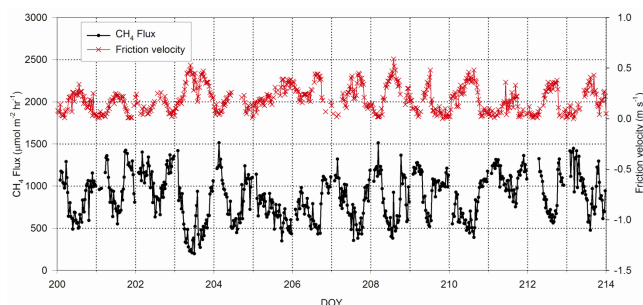


Fig. 2. Time series of half-hourly friction velocity and CH₄ flux between DOY 200 and 214 in 2009 using an autochamber at a sedge-dominated hollow as an example. Other sites showed similar patterns, though the magnitude differed among sites.

sample sizes. The relationships were stronger in the sedge-dominated chambers, with correlation coefficients ranging from -0.18 to -0.55 . Apart from using the instantaneous CH₄ fluxes, we also rank ordered and binned the flux data by u_* into 20 groups (u_* range: 0 – 0.72 m s⁻¹, $N = 188$ – 218 for each group) to examine the relationship between u_* and CH₄ flux. Negative relationships between the two are clearly seen from all the three differently located chambers (Fig. 3). As mean u_* increased from 0.01 to 0.47 m s⁻¹, mean CH₄ flux decreased by 76.5 % from 204 to 48 μmol m⁻² h⁻¹ from the shrub hummock chamber, by 71.0 % from 967 to 280 μmol m⁻² h⁻¹ from the sedge hollow chamber, but only

by 32.1 % from 523 to 355 μmol m⁻² h⁻¹ from the shrub hollow chamber.

We also conducted correlation analysis to determine whether u_* had a significant relationship with autochamber CO₂ efflux, as was the case with CH₄ flux. We used nighttime CO₂ efflux measurements for this analysis to avoid the confounding effects of simultaneous CO₂ uptake and release. Nighttime CO₂ effluxes measured in all the autochambers were significantly and negatively correlated with u_* , with even stronger relationships than CH₄ fluxes (Table 3). Correlation coefficients obtained from sedge-dominated chambers were between -0.40 and -0.80 , while those from shrub-dominated chambers were between -0.29 and -0.78 . Moreover, the rank ordered and binned autochamber CO₂ effluxes (u_* range: 0 – 0.50 m s⁻¹, $N = 82$ – 107 for each of the 15 groups) showed a decreasing trend at all three locations as u_* increased (Fig. 4). Similar to CH₄ flux, we found that the extent of decrease in nighttime CO₂ efflux with u_* was smallest at the shrub hollow, with only a drop of 40.4 % from 9.9 to 5.9 mmol m⁻² h⁻¹, compared to a reduction of 54.2 % from 14.4 to 6.6 mmol m⁻² h⁻¹, and of 58.9 % from 14.1 to 5.8 mmol m⁻² h⁻¹ at the shrub hummock and sedge hollow respectively, as u_* rose from 0.01 to 0.31–0.33 m s⁻¹. The range of u_* was smaller for CO₂ than CH₄ effluxes, because highly turbulent conditions were dominant during the daytime and largely excluded from the nighttime CO₂ efflux data set.

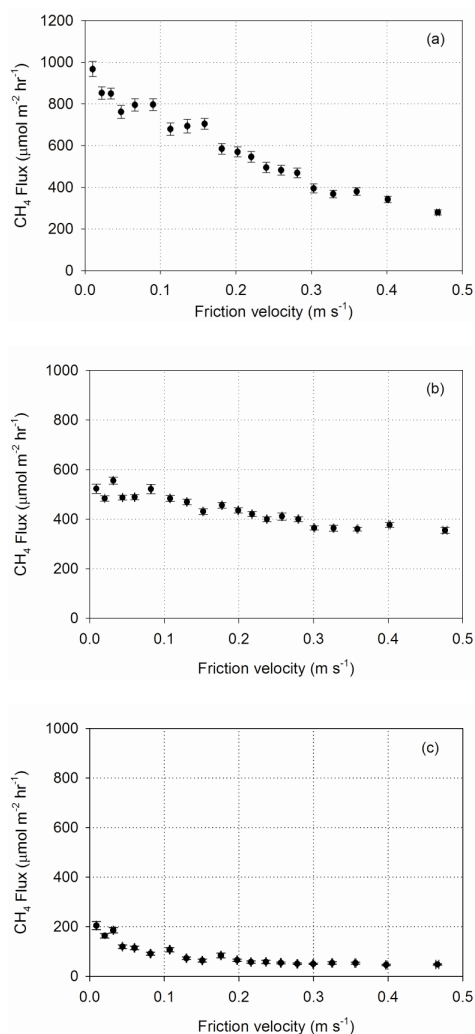


Fig. 3. Relationship between half-hourly friction velocity and autochamber CH₄ flux from (a) sedge-dominated hollow, (b) shrub-dominated hollow, and (c) shrub-dominated hummock between June and September 2009. Fluxes were rank ordered and binned into 20 groups by friction velocity ($N = 188$ – 218 for each group). Error bar indicates ± 1 standard error.

3.2 Atmospheric turbulence and surface peat CO₂ concentration gradient

Ideally, we would have liked to analyze the influence of atmospheric turbulence on the concentrations of CH₄ in the peat profile, but it is very difficult to obtain non-destructive high frequency samples. It is possible that a membrane probe like those of Mastepanov and Christensen (2008) would be capable of continuous monitoring of subsurface CH₄ concentrations but we are unaware of this kind of probe being tested and subsequently used in peatlands. Instead, we investigated the influence of turbulence on gas dynamics in peat pore space by examining the relationship between half-hourly u_* and pore space CO₂ concentration gradient in the

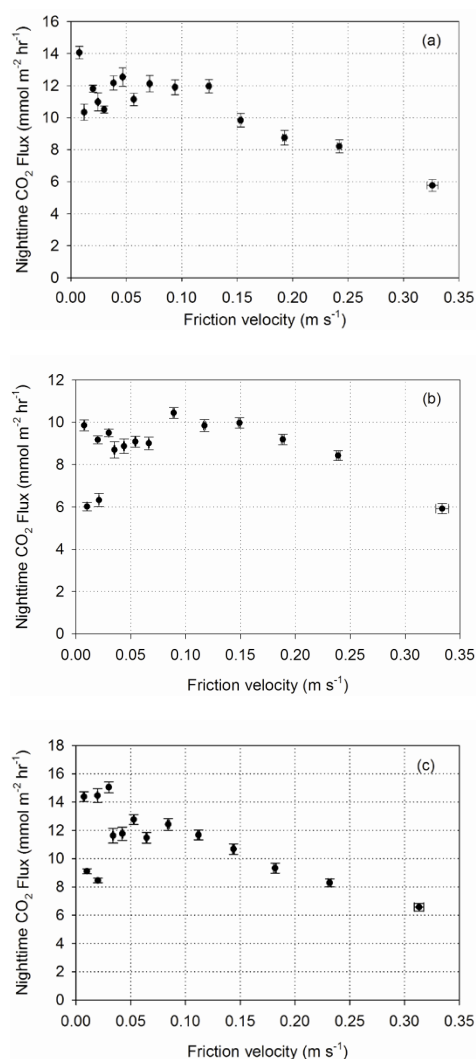


Fig. 4. Relationship between half-hourly friction velocity and autochamber nighttime CO₂ flux from (a) sedge-dominated hollow, (b) shrub-dominated hollow, and (c) shrub-dominated hummock between June and September 2009. Fluxes were rank ordered and binned into 15 groups by friction velocity ($N = 82$ – 107 for each group). Error bar indicates ± 1 standard error.

top 20 cm of peat measured between June and September 2009. Figure 5 shows a general negative relationship between u_* and the rank ordered and binned (u_* range: 0– 0.72 m s⁻¹, $N = 224$ – 234 for each of the 20 groups) surface peat CO₂ concentration gradient. As u_* increased slightly under calm condition from 0.01 to 0.06 m s⁻¹, the mean CO₂ concentration gradient increased correspondingly from 21.3 to 26.4 μmol mol⁻¹ cm⁻¹. Yet, as u_* further increased from 0.06 to 0.47 m s⁻¹, we observed a consistent and substantial decrease in mean CO₂ concentration gradient from 26.4 to 3.0 μmol mol⁻¹ cm⁻¹. Moreover, the half-hourly surface peat CO₂ concentration gradient was strongly and negatively correlated with u_* ($r = -0.56$, $p < 0.01$, $N = 4490$).

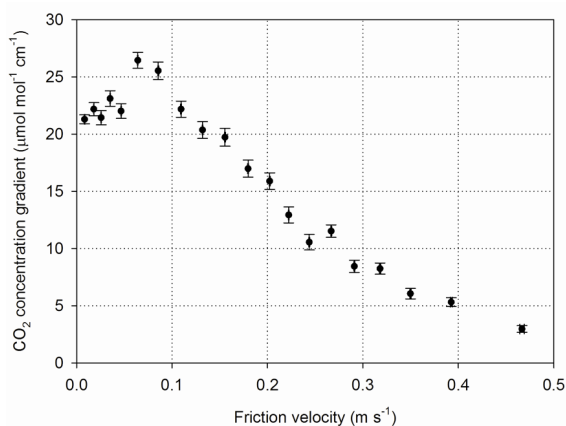


Fig. 5. Relationship between half-hourly friction velocity and CO₂ concentration gradient in the top 20 cm peat of a hummock between June and September 2009. Gradients were rank ordered and binned into 20 groups by friction velocity ($N = 224\text{--}234$ for each group). Error bar indicates ± 1 standard error.

3.3 Effects of chamber deployment period on measured fluxes

We operated two autochambers with an extended deployment period of 30 min (i.e. 24 lid closures/chamber/day) for four days and investigated how the fluxes derived from the rate of change in chamber headspace gas concentrations varied over 19 successive 1.5-min periods. Figure 6a and c show that autochamber CH₄ fluxes from the sedge- and shrub-dominated lawns became relatively constant starting from the 9th and 7th 1.5-min periods respectively, regardless of whether the flux increased or decreased during the initial period after chamber closure. Nighttime CO₂ efflux rates from both the sedge- and shrub-dominated chambers decreased consistently at the beginning of the measurement and then generally reached a stable level at approximately the 9th 1.5-min period (Fig. 6b and d). Relative to the difference in flux between the 1st and 2nd periods, the mean absolute difference in CH₄ flux and nighttime CO₂ flux between the 8th and 9th periods was only 8–16% and 16–23%, respectively for a given chamber. Figure 7 depicts the typical change in headspace CO₂ and CH₄ concentrations over time during chamber deployment in calm and highly turbulent conditions.

Figure 8 shows the time series of friction velocity and CH₄ flux from the sedge-dominated chamber calculated during various 1.5-min periods over the 30 min of chamber deployment between DOY 177 and 181 (u_* range: 0.01–0.51 m s⁻¹). Fluxes determined in the first 1.5-min period, equivalent to those obtained with the original protocol using a 2.5-min deployment period, still exhibited a diel pattern that was negatively correlated with u_* . However, for CH₄ fluxes determined in the 9th 1.5-min period and beyond, diel variability and correlation with u_* disappeared. We found

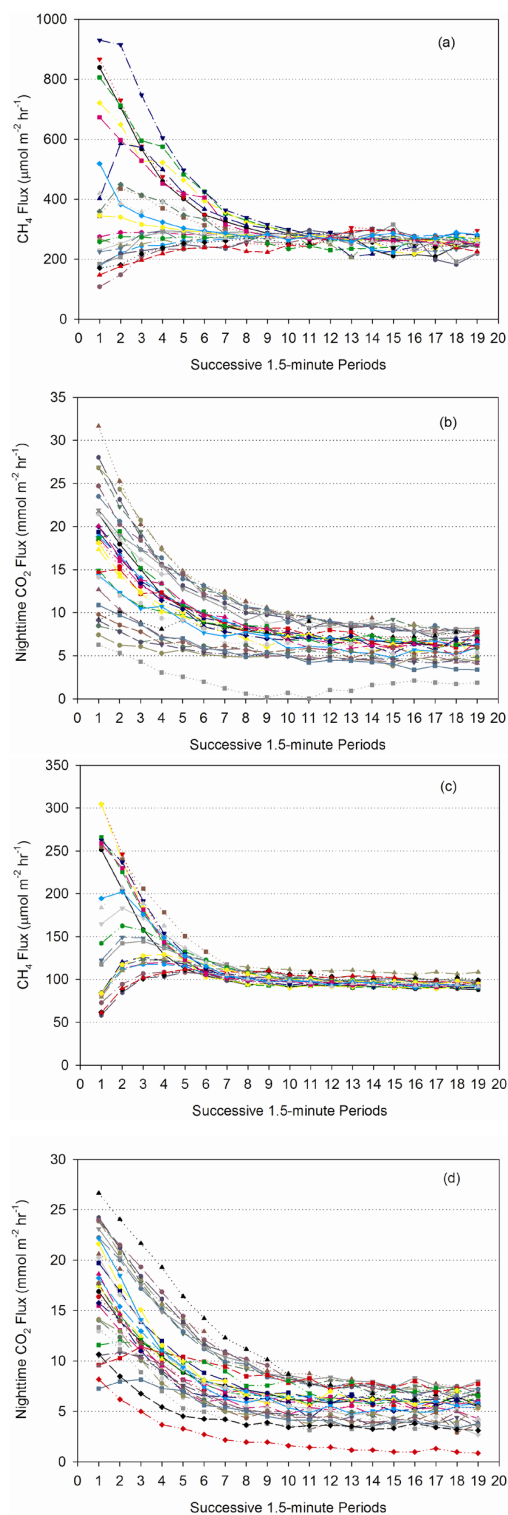


Fig. 6. CH₄ flux (DOY 180) and nighttime CO₂ efflux (DOY 177–181) in 19 successive 1.5-min periods over 30 min of chamber deployment, from (a, b) a sedge-dominated chamber, and (c, d) a shrub-dominated chamber. The different lines represent the replicate flux measurements made during the above-mentioned period.

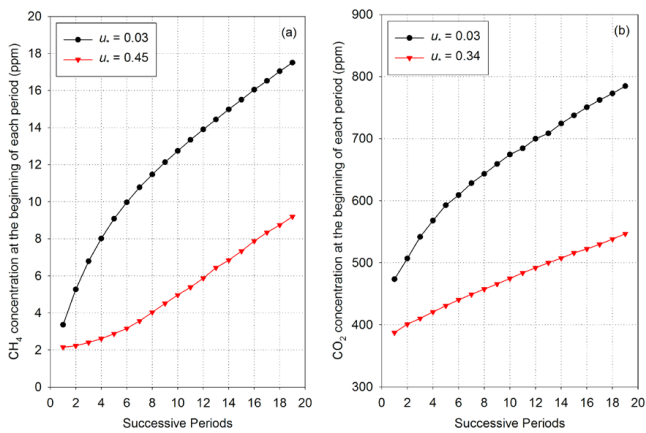


Fig. 7. Examples of the concentration trace in the headspace of a sedge-dominated chamber over 19 successive 1.5-min periods in calm and highly turbulent conditions for (a) CH₄ and (b) CO₂.

that, in calm conditions, fluxes determined in the first 1.5-min period were considerably higher than those in the later periods. In contrast, during times of strong turbulence, CH₄ fluxes obtained in the first 1.5-min period were much lower than those obtained in the 9th 1.5-min period and beyond.

Based on the above results, we assumed that fluxes determined in the 9th 1.5-min period were no longer influenced by the atmospheric turbulence experienced prior to chamber closure and hence were more realistic estimates of the biological fluxes. We then estimated the degree of over- or underestimation of biological fluxes associated with a short deployment period of 2.5 min, by calculating the difference in fluxes determined in the 1st and 9th 1.5-min periods when all the chambers were operated with a 15-min deployment period between 6 July and 15 September 2010. The relationships between u_* and the overestimation of CH₄ and nighttime CO₂ flux at hollow sites were well described by quadratic equations with r^2 values between 0.44 and 0.74 (Fig. 9a–d). We found on average an overestimation of biological CH₄ flux of about 100 % by autochambers in calm conditions. The degree of flux overestimation gradually decreased towards zero as u_* increased up to 0.2 and 0.4 m s⁻¹ at the sedge-dominated and shrub-dominated hollows, respectively (Figs. 9a and 8c). When u_* increased even further, we observed a relatively constant underestimation of biological CH₄ fluxes. Flux underestimation when atmospheric turbulence was high was more pronounced at the sedge-dominated hollow (–57 %) than the shrub-dominated counterpart (–9 %). Similarly, nighttime CO₂ fluxes were overestimated at hollows by about 100 % in calm conditions (Figs. 9b and 8d). As u_* increased to more than 0.5 m s⁻¹, we found a 13–21 % underestimation of nighttime CO₂ flux based on the limited number of measurements made in windy nights. Meanwhile, at the shrub hummock site, the overestimation of CH₄ and nighttime CO₂ fluxes varied greatly for a given u_* , such that relationships with u_* were poorly de-

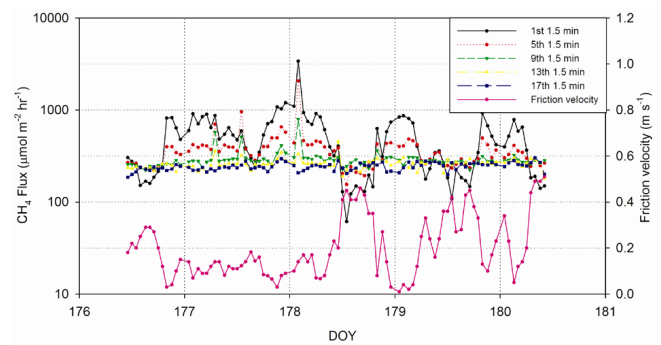


Fig. 8. Time series of friction velocity and CH₄ flux from a sedge-dominated chamber determined from the 1st, 5th, 9th, 13th and 17th 1.5-min periods over 30 min of chamber deployment. Note the logarithmic scale used on the y-axis.

scribed by quadratic equations with low r^2 values of 0.07 and 0.02 respectively.

We calculated the average overestimation of biological CH₄ flux for groups of u_* with a range of 0.1 m s⁻¹ increasing at 0.05 m s⁻¹ intervals based on the results in Fig. 9. When u_* was within a range associated with an average flux overestimation or underestimation of less than 20 %, CH₄ fluxes collected with a 2.5-min deployment period were retained in the data set. The u_* threshold for accepting fluxes was smaller in both magnitude and range for a sedge-dominated (0.15–0.3 m s⁻¹) than a shrub-dominated hollow (0.25–0.6 m s⁻¹). This filtering resulted in a data set of 596 to 3887 CH₄ fluxes per chamber through the 2009 measurement period after removing 51.3 to 92.5 % of the flux measurements per chamber. Figure 10 shows the diel variability of monthly mean CH₄ flux in 2009 from autochambers at the three sites (also illustrated in Fig. 1) after filtering with u_* thresholds. After filtering, the monthly variability of CH₄ fluxes from autochambers was still clear, but much of the diel flux patterns shown in Fig. 1 disappeared.

4 Discussion

4.1 The influence of atmospheric turbulence and chamber deployment period on autochamber gas fluxes

Friction velocity is commonly used as a measure of atmospheric turbulence and momentum transfer between the atmosphere and plant canopy (Foken, 2008). While we found significant, negative correlations between u_* and autochamber CH₄ and nighttime CO₂ fluxes (Tables 2 and 3), previous studies have reported a positive effect of turbulence on ecosystem gas fluxes. Using the eddy covariance technique, near-surface turbulence was shown to enhance ecosystem-level CH₄ fluxes from a Siberian polygonal tundra with a high surface coverage of water bodies (Wille et al., 2008) and

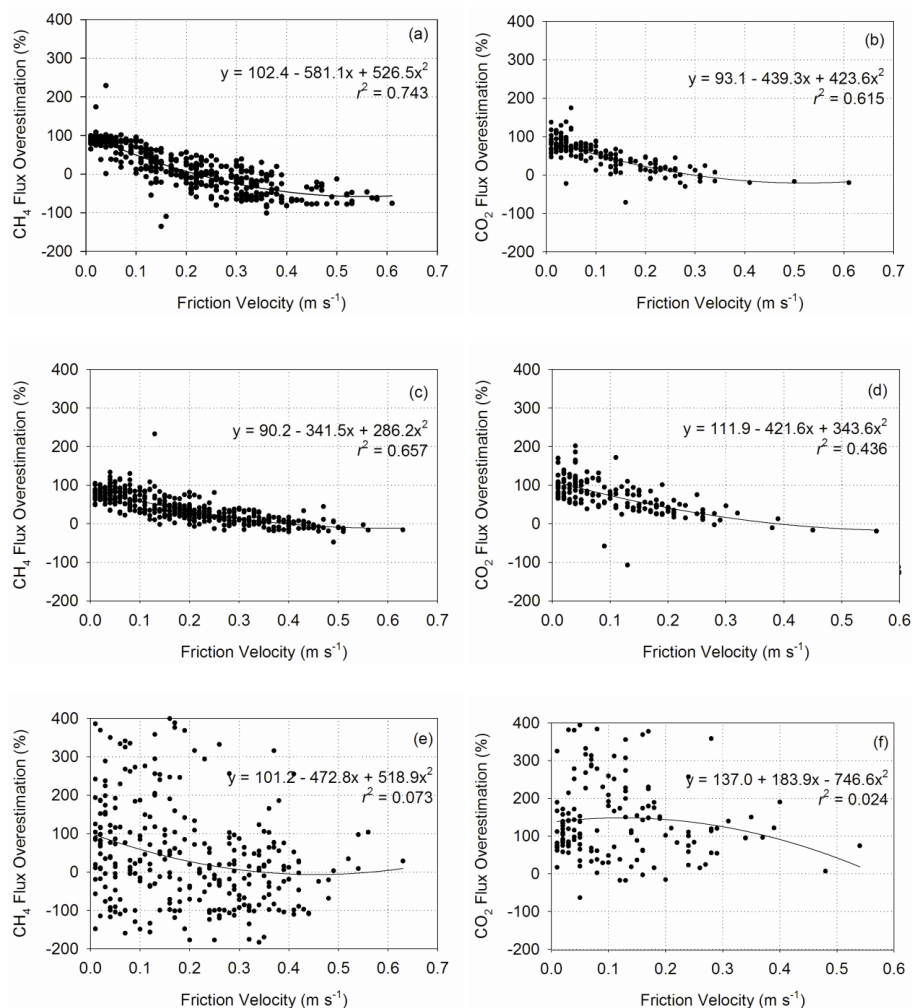


Fig. 9. Percent overestimation of autochamber CH₄ and nighttime CO₂ flux associated with the use of a short deployment period of 2.5 min as a function of friction velocity, from (a, b) sedge-dominated hollow, (c, d) shrub-dominated hollow, and (e, f) shrub-dominated hummock, assuming that fluxes calculated based on headspace concentration change in the 9th 1.5-min period were more realistic.

a Russian boreal peatland with a water table above the peat surface during the snowmelt period (Gažovič et al., 2010), due to turbulence-induced gas transfer across the air-water interface and release of gas bubbles that were adhered to the water surface. This mechanism does not occur at Mer Bleue because of the much lower water table. Measurements with closed dynamic chambers equipped with vents also demonstrated a higher CO₂ efflux from soils of a deciduous forest and a temperate cropland as wind speed increased (Bain et al., 2005; Suleau et al., 2009). As strong winds blow across the chamber vent tube, a pressure deficit develops inside the chamber (a phenomenon known as the Venturi effect), which is compensated for by mass flow of CO₂-enriched air from soils into the chamber headspace (Conen and Smith, 1998). Although we had no available data on chamber pressure to exclude the possibility of a Venturi effect, we did not ob-

serve enhanced gas fluxes under windy conditions at the Mer Bleue bog.

Using an open dynamic chamber that enabled changes in atmospheric pressure to be transmitted to the soil surface, Rayment and Jarvis (2000) found that atmospheric turbulence enhanced soil CO₂ efflux from a boreal black spruce forest, with stronger effect at sites with a thicker layer of porous peat. Moreover, Subke et al. (2003) observed a positive correlation between the standard deviation of horizontal wind velocity and CO₂ efflux rate from a spruce forest soil by employing the same chamber system. They suggested that the increase in soil CO₂ fluxes was a result of pressure pumping induced by wind actions. When wind passes over an uneven surface or changes in speed and direction, high-frequency pressure fluctuations over the soil surface are created. The presence of static horizontal pressure difference can then cause a mass flow of gas horizontally and

Table 3. Correlation coefficients (r) between friction velocity and autochamber nighttime CO₂ efflux stratified by air temperature in 5 °C classes from June to September 2009^a.

Chamber	0–5 °C		5–10 °C		10–15 °C		15–20 °C		20–25 °C	
	r	N	r	N	r	N	r	N	r	N
Sedge-dominated										
1	–0.70**	134	–0.74**	278	–0.71**	453	–0.73**	440	–0.80**	86
2	–0.40**	127	–0.48**	255	–0.40**	403	–0.44**	369	–0.77**	77
4	–0.41**	126	–0.51**	242	–0.44**	393	–0.49**	371	–0.52**	69
7	–0.57**	102	–0.63**	216	–0.60**	390	–0.58**	423	–0.67**	84
Shrub-dominated hollow										
8	–0.29**	132	–0.50**	277	–0.48**	453	–0.41**	440	–0.54**	86
10	–0.40**	127	–0.49**	263	–0.34**	443	–0.49**	439	–0.66**	86
Shrub-dominated lawn										
3	–0.53**	134	–0.67**	278	–0.58**	453	–0.66**	440	–0.70**	86
9	–0.65**	103	–0.71**	243	–0.62**	406	–0.51**	399	–0.70**	82
Shrub-dominated hummock										
5	–0.33**	129	–0.56**	248	–0.42**	381	–0.36**	393	–0.60**	80
6	–0.48**	132	–0.55**	276	–0.55**	449	–0.64**	439	–0.78**	86

^a r = correlation coefficient; N = sample size.

** Significant at the 0.01 level.

vertically in the soil and eventually out to the atmosphere along the pressure gradient (Takle et al., 2004). This explains the decrease in the amount of CO₂ stored in the soils of a permanent grassland (Flechard et al., 2007) and pine forest (Maier et al., 2010) with increasing turbulence. Similarly at Mer Bleue, the CO₂ concentration gradient in the top 20 cm of peat was greatly diminished under highly turbulent conditions compared to calm conditions (Fig. 5). Hirsch et al. (2004) also reported a negative relationship between u_* and CO₂ concentration gradient in the top 5 cm litter layer of a boreal forest but attributed this to wind flushing or directly penetrating into the highly porous and air-filled layer near the moss surface. Since the Mer Bleue bog has a low water table and high surface peat porosity, the large volume of air-filled peat pore space may facilitate wind flushing into the surface peat in addition to turbulence-induced pressure pumping, resulting in depletion of accumulated gases and reduction of the belowground gas concentration gradient.

Although atmospheric turbulence was not expected to alter the closed environment inside the chamber headspace, between measurements (over 90 % of time), the chamber was left open and hence the surface peat inside the collar was subject to pressure pumping and wind flushing effects under highly turbulent conditions. With the chamber closed, the diffusive CH₄ and nighttime CO₂ effluxes were small (Figs. 3 and 4) owing to a reduced concentration gradient caused by turbulence before chamber deployment. Given the short deployment period of 2.5 min, there was insufficient time for

the diffusive concentration gradient to adjust to the new turbulence conditions and associated transport resistances, and much of the gases produced were stored in peat rather than released into the chamber headspace. Using a longer chamber deployment period of 30 min, we show that CH₄ flux rate obtained in turbulent conditions was initially low, but increased over time and reached a stable level ~ 13 min after chamber closure (Figs. 6 and 7). The attainment of constant flux suggested that, at this time, the net rate of gas production (i.e. production minus consumption) in the peat matched that of diffusive flux from the peat into the chamber headspace. Assuming fluxes determined in the 9th 1.5-min period best represented the net biological gas production rates, we found underestimations of 13–21 % for CO₂ and 9–57 % for CH₄ fluxes for a given chamber associated with measurements made during strong turbulence ($u_* > 0.5 \text{ m s}^{-1}$) with a deployment period of 2.5 min (Fig. 9). Kutzbach et al. (2007) observed that, for 20–40 % of their peatland flux measurements, the curves of headspace concentration evolution over time had a concave-down shape that could not be explained by the exponential model developed based on biophysical theory. Our findings suggest that their measurements showing an increase in CO₂ efflux over time might have been made when atmospheric turbulence was strong, such that belowground concentration gradients were small due to wind flushing and/or pressure pumping before chamber deployment.

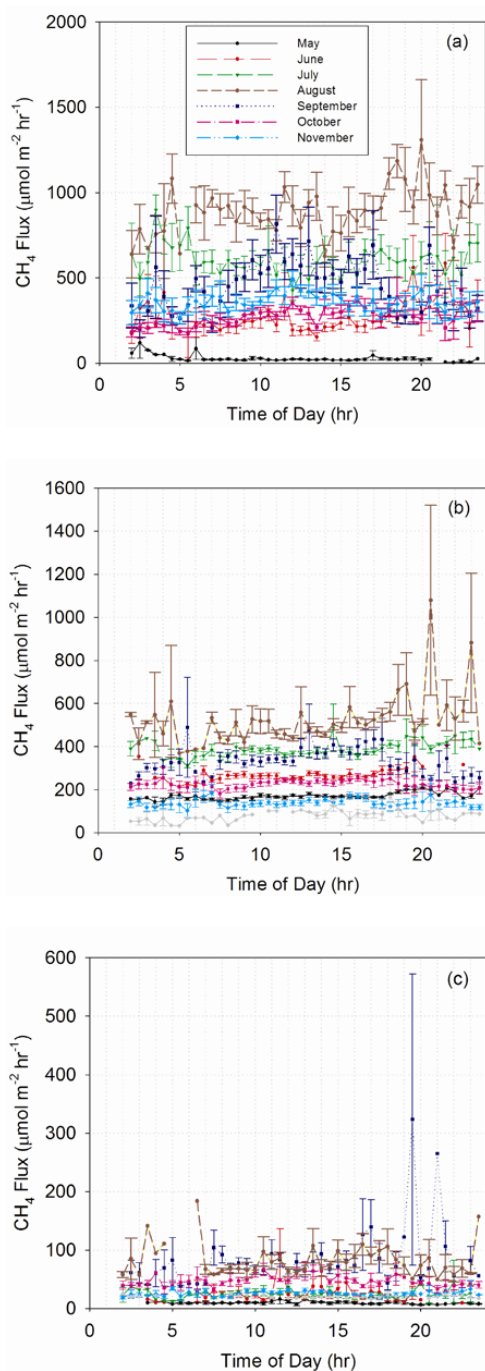


Fig. 10. Diel variability of monthly mean autochamber CH_4 flux from (a) sedge-dominated hollow, (b) shrub-dominated hollow, and (c) shrub-dominated hummock in 2009 after filtering with thresholds in friction velocity. Error bar indicates ± 1 standard error.

On the other hand, we observed substantial overestimation of both biological CH_4 and nighttime CO_2 effluxes of near 100 % in calm conditions when u_* was low (Fig. 9). Results using an extended deployment period show that measured fluxes were very high immediately after chamber closure and

then decreased rapidly over the first 13 min before stabilizing (Fig. 6). It has been suggested that fluxes measured by closed chambers tend to decrease continuously with time, as build-up of gases in the chamber headspace reduces the diffusive concentration gradient, which in turn lowers the diffusive flux as a feedback from the chamber to soil (Livingston et al., 2005). Yet, such chamber feedback was unlikely to be the major cause of flux decrease seen at the beginning of our measurements, since fluxes were maintained at a relatively constant level after the initial period rather than exhibiting a further decreasing trend. We suggest that the large gas flux initially obtained was caused by chamber-induced disturbance. In calm conditions, molecular diffusion dominates gas transport and a thick atmospheric interfacial layer with steep concentration gradient develops near the peat surface. As the chamber closes, the fan equipped on the chamber lid and the air stream circulated through the sample tubing to the gas analyzers facilitate mechanical air mixing in the headspace and disrupt the interfacial layer, thus instantaneously lowering the gas concentration just above the peat surface. This immediately leads to a sharp increase in gas concentration gradient from the peat to the atmosphere and hence the increase in gas flux rate (Hutchinson et al., 2000). Based on manual chamber measurements in a boreal peatland, Schneider et al. (2009) found an 18–31 % overestimation of cumulative seasonal nighttime ecosystem respiration if CO_2 fluxes measured during calm conditions were included in the data set. A test of this hypothesis would be to remove the fan and determine fluxes over calm nights by measuring and integrating the concentration profile over the height of the chamber headspace, but we have not done this experiment to date.

The effects of turbulence on chamber flux measurements vary both spatially and temporally. At hollows, the diel difference in CH_4 flux measured with a short deployment period and the underestimation of biological gas fluxes during highly turbulent conditions were both larger at sedge-dominated than shrub-dominated sites. *Eriophorum* sedges at the Mer Bleue bog possess aerenchymatous tissues that act as gas conduits between the soil and atmosphere (Greenup et al., 2000). By generating a pressure gradient, turbulence can induce a plant-mediated convective flow of gases from deep in the root zone to the atmosphere via the aerenchyma (Armstrong et al., 1996). In addition, the large pool of CH_4 stored belowground causes the sedge sites to be highly susceptible to advective transport mechanisms (Forbrich et al., 2010). As a result, the pore space gas concentration gradient and transient diffusive flux measured by autochambers in windy conditions were reduced to a much greater extent at sedge-dominated sites compared to sites dominated by shrubs lacking aerenchymatous tissues. Atmospheric turbulence had the smallest effect on gas fluxes measured at shrub-dominated hollows, owing to the presence of a high water table and the absence of plant-mediated transport. The smaller volume of air-filled pore space for the full peat profile implies that effective diffusivity is reduced and only a small amount of gas

enriched in CO₂ and CH₄ is released from soil into the atmosphere subsequent to chamber disturbance effects in calm conditions (Schneider et al., 2009). Moreover, the wind flushing/pressure pumping effect is less pronounced at hollows as the air-filled peat layer that stores gas for potential mass flow is thinner. At hummocks, we found a substantial decrease in CH₄ and nighttime CO₂ fluxes in highly turbulent conditions (Figs. 3 and 4), due to the presence of a thick peat layer with high air-filled porosity. However, flux measurement bias associated with a short chamber deployment period varied considerably at hummocks even under the same u_* (Fig. 9), possibly because of the inherently high variance of CO₂ flux (Schneider et al., 2009) and small magnitude of CH₄ flux. Temporally, the diel difference in CH₄ flux was largest in the mid-growing season around August and September, because a large amount of CH₄ was produced by active methanogenesis during this period when peat temperature and root exudation were relatively high. Consequently, the amount of CH₄ stored in peat pore space was large (Blaufus et al., 2007), thereby enhancing the effects of wind flushing/pressure pumping and chamber-induced disturbance on flux measurement bias.

4.2 Implications for chamber flux measurements

Closed chambers are only capable of measuring diffusive and ebullition flux but not mass flow and hence cannot provide a good estimate of the actual rate of peatland-atmosphere gas exchange particularly in times of strong turbulence. Rayment and Jarvis (2000) reported a 2–14 % underestimation of soil CO₂ efflux from a boreal forest when the influence of turbulence was not taken into account in flux determination. Some researchers have addressed this issue by correcting the surface gas fluxes measured by chambers with the pore space gas storage fluxes (Hirsch et al., 2004; Maier et al., 2010). Yet, changes in the amount of gas stored in pore space belowground depend on both present and antecedent meteorological conditions, leading to difficulty in using the strength of atmospheric turbulence to estimate the contribution of mass flow to the overall flux (Subke et al., 2003). A brief gust of wind will cause a larger change in gas storage if it follows a calm period than if it follows a prolonged period of strong turbulence which would have already depleted the gas stocks within the pore space. Meanwhile, the reduction in concentration gradient created by the gust of wind in both cases implies that gas fluxes obtained by closed chambers with a short deployment period will likely be low. Instead, we suggest that closed chambers can be used to estimate the net biological gas production rate when deployed for a long enough time that the initial turbulence-related effects are no longer observed. However, it is likely that the net CH₄ production rate determined will be overestimated if ebullition occurs during a chamber measurement, as gas bubbles containing previously generated CH₄ are released into the atmosphere at a much greater rate than diffusion alone.

Attempts have been made to compare upscaled chamber fluxes to ecosystem level fluxes measured by eddy covariance system in peatlands (e.g. Laine et al., 2006; Riutta et al., 2007; Forbrich et al., 2011), but such comparisons should take into account the potential artefacts of both chamber and eddy covariance measurements. In highly turbulent conditions, eddy covariance may measure a higher gas exchange rate than the biological flux due to enhanced gas transport from soil induced by pressure changes (Gu et al., 2005), while closed chambers miss the mass flow component and may measure smaller fluxes when deployed for a short period because of the transient reduction in concentration gradient, or in some cases, may measure larger fluxes due to pressure pumping as winds blow over the vent tube (Conen and Smith, 1998). On the other hand, in calm conditions, the eddy covariance method underestimates biological gas fluxes because of insufficient turbulent mixing, presence of drainage flows, and errors in estimating the rate of change in gas storage below the height of eddy covariance instrumentation (Baldocchi, 2003; Aubinet, 2008), while chamber deployment perturbs the atmospheric boundary layer and may result in flux overestimation. Using the same autochamber system as ours in a boreal peatland, Cai et al. (2010) found higher seasonally integrated respiration rates from chambers than from eddy covariance, which might be partly caused by chamber artefacts that could result in overestimated CO₂ fluxes in calm nights.

Chamber deployment period is an important consideration when making flux measurements. It is preferable to deploy chambers for a period as short as possible to minimize plant stress caused by increasing temperature and build-up of moisture in the headspace over time. Moreover, the use of a short deployment period diminishes chamber feedback effects associated with reducing concentration gradients between the soil and headspace (Davidson et al., 2002), enables a linear increase in headspace gas concentration for flux determination (Kutzbach et al., 2007) and reduces the errors of flux estimates from soils with non-uniform physical properties through the profile (Venterea and Baker, 2008). Furthermore, shortening the deployment period by half in an automated chamber system implies a doubling of the number of measurements that can be made. In spite of all the advantages associated with a short deployment period, we show at the Mer Bleue bog that initial changes in headspace concentration after chamber closure were greatly affected by turbulence conditions prior to chamber deployment and thus should not be used in flux calculation. This is especially important for the application of non-linear regression in estimating fluxes. Although non-linear regression takes into account the effects of chamber feedback, it is highly sensitive to the initial slope of headspace gas concentration versus time (Kutzbach et al., 2007; Forbrich et al., 2010). It should be noted that the time it takes for the measured flux to reach a stable level unaffected by pre-deployment turbulence conditions is probably a function of peat porosity, water table,

plant type and fan speed, and hence should be determined for specific sites and chamber systems.

The calculation of gas fluxes from concentration change in chamber headspace often assumes implicitly that the headspace turbulence is constant and equal to ambient conditions during deployment (Kutzbach et al., 2007). Yet, this assumption can hardly be met in the field, as atmospheric turbulence is always changing while the turbulence inside the headspace of a closed chamber is constant. Peatland CH₄ flux is commonly quantified by deploying manual static chambers and withdrawing air samples in the headspace periodically (e.g. every 5 min) over the deployment period (e.g. 25 min) for subsequent CH₄ analysis in the laboratory (e.g. Pelletier et al., 2007; Moore et al., 2011). Based on an automatic, closed, dynamic chamber system measuring gas concentrations at 1 Hz, our findings suggest that CH₄ concentration change will be most influenced by turbulence during the initial 5 min and then progressively less with time. Such variations in CH₄ flux rates during deployment of manually sampled static chambers are difficult to detect because of the small number of data points. Similarly, the turbulence-related impacts on CO₂ efflux are hardly noticed in measurements with manual dynamic chambers when the duration of deployment is short (~2.5 min), although the infrared gas analyzer typically measures CO₂ concentrations with a high temporal resolution (e.g. Bubier et al., 2003; Pelletier et al., 2011). Further studies should be done to investigate the effect of turbulence on gas concentration evolution in the headspace of manual chambers, for example by sampling air and analyzing for CH₄ concentration every minute for a half hour, and monitoring the change in headspace CO₂ concentration in darkness over a longer deployment period. This will allow us to test the assumption of a constant rate of headspace concentration increase throughout the deployment period used in determining CO₂ and CH₄ effluxes.

Since fluxes are underestimated and overestimated in high and low turbulence conditions respectively, closed chambers when deployed only for a short time are most likely measuring the “true” biological fluxes at some intermediate atmospheric turbulence levels. The friction velocity thresholds we derived to filter the CH₄ fluxes measured with a 2.5-min deployment period were successful in eliminating the diel pattern of CH₄ flux and could be potentially used to estimate the biological CH₄ flux. However, since the nighttime CO₂ fluxes were typically measured in calm conditions and hence overestimated, a filtering approach similar to the one used for CH₄ might have removed the bulk of available data. Instead, we suggest estimating the biological CO₂ source strength by correcting all the nighttime CO₂ efflux data based on the empirical relationship between measurement bias (i.e. % overestimation) and friction velocity (Fig. 9). We do not filter or correct the daytime CO₂ flux data as carbon exchange during this period is dominated by plant uptake. However, as daytime periods are often fairly turbulent, the diffusive soil respiration component of the chamber

CO₂ flux is likely underestimated. Based on an aggregated data set from chamber measurements at five sites, Frohling et al. (1998) reported a mid-season average ecosystem respiration of 2.0 μmol m⁻² s⁻¹ and maximum net ecosystem CO₂ exchange of -2.5 μmol m⁻² s⁻¹ for northern bogs. Using these values, if chamber CO₂ efflux is underestimated by 20% during turbulent conditions, then the magnitude of maximum daytime net ecosystem CO₂ exchange measured by closed chambers at Mer Bleue with a deployment period of 2.5 min will be overestimated by 16%.

5 Conclusions

We demonstrated that the diel pattern of autochamber CH₄ flux was caused predominantly by a change in the physical processes of gas transport in relation to atmospheric turbulence. CH₄ and nighttime CO₂ effluxes measured with a 2.5-min deployment period were negatively correlated with u_* . In highly turbulent conditions, underestimation of transient fluxes was caused by a combination of an artificial and sudden decrease in headspace turbulence by chamber deployment, as well as a reduction of diffusive concentration gradient from wind flushing and/or pressure pumping, as shown by our pore space CO₂ concentration data in near-surface peat. In calm conditions, chamber-induced disturbance of the atmospheric interfacial layer likely steepened the gas concentration gradient between the peat and atmosphere, which subsequently increased the transient gas flux. This measurement artefact associated with a difference in headspace turbulence before and during chamber deployment created a bias in fluxes measured in the initial 13 min after chamber closure. The constant chamber fluxes obtained after this initial period can be used to indicate the strength of biological source of CO₂ and CH₄, as a quasi-equilibrium between the net rates of gas production and gas exchange across the peat surface is likely attained. Meanwhile, the pore space gas dynamics in the peat profile deserves further attention for assessing the influence of a large pool of gases in the deeper peat layers on the rate of gas exchange across the peat surface.

We expect turbulence-related measurement bias to be more significant in ombrotrophic bogs than minerotrophic fens, because of the presence of a lower water table and higher air-filled peat porosity that provides an environment more conducive to mass flow of gases from the peat pore space. A pressure pumping effect (or ventilation) has been observed as well in other ecosystems that have porous substrates for gas storage, e.g. boreal forests with moss in the understory (Hirsch et al., 2004), snowpack-covered meadows and forests (Massman and Frank, 2006), and carbonate ecosystems with subterranean pores and cavities (Were et al., 2010). Fluxes from closed chambers in settings like these should be interpreted with caution as they may not quantify the actual rate of gas exchange between soils and the atmosphere. Chamber deployment period should be carefully

selected particularly for ecosystems with porous substrates such that headspace concentration data are collected beyond the initial period affected by chamber artefacts. The time required for chamber fluxes to reach a constant level should be determined for each site and chamber system before actual flux measurement in the field. This bias is not only limited to closed autochambers, but may be more difficult to quantify with a manual, closed chamber system owing to the often poorer temporal resolution of headspace concentration data. If the chamber is deployed for a period too short to eliminate this measurement artefact, we suggest filtering the CH₄ data set based on friction velocity thresholds and correcting the nighttime CO₂ data set based on established empirical relationships between measurement bias and u_* to estimate the biological fluxes of these gases.

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