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# Gross photosynthesis explains the ‘artificial bias’ of methane fluxes by static chamber (opaque versus transparent) at the hummocks in a boreal peatland

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## Abstract

The closed chamber technique has been widely employed to detect methane emissions, despite little being known about whether the absence or presence of light will impact the flux estimation. Here, we employed a laser greenhouse gas analyzer with an opaque—transparent chamber pair to measure the methane emission rate in a boreal peatland complex. Microtopography (i.e., hummocks and hollows) in natural and drained peatlands, and plant communities (i.e., grasses and shrubs) in a pasture converted from natural peatlands, were considered to cover the local heterogeneity. Our results indicated that opaque chambers ( $0.58\text{--}0.78\text{ g CH}_4\text{ m}^{-2}$  during the growing season) measured a significantly higher ( $\sim 2\text{--}3$  times) methane emission at the hummocks than transparent chambers ( $\sim 0.24\text{ g CH}_4\text{ m}^{-2}$ ); however, a similar phenomenon was not found at the hollows or at other measurement plots. Gross photosynthesis explained 44%–47% of the temporal variation of the ‘artificial bias’ (the difference in methane flux obtained by the opaque versus transparent chambers) at the hummocks. Additionally, both water table depth and surface soil moisture significantly explained spatial variations of methane emissions. Our study suggests that microtopography has a significant influence on the artificial bias in methane emission estimation and the artificial properties of a chamber (transparency/opacity) method can be vitally important in some cases (i.e., hummocks), and negligible in others (i.e., hollows). The observed connection between the photosynthesis process and the ‘artificial bias’ of closed chambers (opaque versus transparent) can be used to improve methane flux modeling. Separate parameterization schemes are needed for methane transportation under the presence or absence of light.

Keywords: methane oxidation, *Sphagnum* moss, microtopography, oxygen recycling, transparent chambers, opaque chambers, boreal peatlands

## 1. Introduction

Understanding the dynamics of methane ( $\text{CH}_4$ ) emissions is of paramount importance because  $\text{CH}_4$  has 34 times the

global warming potential of carbon dioxide ( $\text{CO}_2$ ) (IPCC 2013) and is currently the second most important anthropogenic greenhouse gas (Bridgman *et al* 2013). Global wetlands are the largest single atmospheric source of natural methane, and they were estimated to emit  $\sim 100\text{--}200\text{ Tg yr}^{-1}$   $\text{CH}_4$  into the atmosphere (Neef *et al* 2010, Dlugokencky *et al* 2011). Further, it was found that freshwater methane emissions can even offset the continental carbon sink (Bastviken *et al* 2011). Wetland emissions dominated the inter-



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annual variability of atmospheric methane sources between 1984 and 2003 (Bousquet *et al* 2006). Therefore, it is critically important to accurately estimate methane emission from natural wetlands.

A variety of approaches have been employed to detect the methane exchanges between the biosphere and the atmosphere (Wang *et al* 2012), such as chamber enclosure techniques (Moore & Roulet 1991, Altor & Mitsch 2008, Mastepanov *et al* 2008, Christiansen *et al* 2011, Strack & Zuback 2013, Sabrekov *et al* 2014), eddy covariance techniques (Rinne *et al* 2007, Wille *et al* 2008, Kroon *et al* 2010, Wang *et al* 2012), flux-gradient techniques (Edwards *et al* 2001), and CH<sub>4</sub> mixing ratio measurements (e.g., Dlugokencky *et al* 2009). Among them, chamber enclosure techniques have been widely employed to measure the CH<sub>4</sub> flux of a variety of ecosystems in the field because of the simplicity and relatively inexpensive nature of the method (Cao *et al* 2008, Davidson *et al* 2008, Mastepanov *et al* 2008, Guckland *et al* 2009). Data from chamber based measurements have been taken as an important source of examining spatial variability and environmental controls of methane emission from various ecosystems, including wetland ecosystems. However, either opaque (Davidson *et al* 2008, Guckland *et al* 2009) or transparent (Cao *et al* 2008, Mastepanov *et al* 2008) chambers were employed to conduct the chamber enclosure measurement, even though clear plastic chambers can lead to high temperatures as a result of a long covering period (Chanton & Whiting 1995), while an opaque chamber might impact CH<sub>4</sub> emission estimation over 30 min coverage since stomata started to close after 30 min (Morrissey *et al* 1993).

Many studies mentioned the potential artifacts (Silvola *et al* 2003, Hirota *et al* 2004) of the opaque chamber. The opaque chamber will apparently block the light from the chamber and thus may stop or slow ecosystem processes, such as photosynthesis, transpiration, and evaporation. As a result, the blockage of light under opaque chambers potentially impacts the production, transportation, or emission process of CH<sub>4</sub>. For example, plants take up and transpire water containing dissolved methane (Nisbet *et al* 2009), while light levels are tightly connected to stomata openness and thus transpiration rates (Shimazaki *et al* 2007). The absence of photosynthesis will slow the transport of the substrate to the rhizosphere, and thus reduce the substrate supply to the methanogenesis process. As a result, the reduction in the substrate supply will impact the methane production, because the production of CH<sub>4</sub> is highly constrained by the substrate availability (Kankaala & Bergström 2004). Methane oxidation activated by the light (Graetzel *et al* 1989), and methane emissions from wetlands regulated by the light (King 1990) were also reported. *Sphagnum* moss was also reported to consume CH<sub>4</sub> through symbiosis with partly endophytic methanotrophic bacteria, providing carbon for photosynthesis in the peat bogs (Raghoebarsing *et al* 2005, Kip *et al* 2010). However, the heating effects of the transparent chamber might cause a faster or slower emission rate of CH<sub>4</sub>, as both production and consumption of CH<sub>4</sub> are regulated by temperature (Frolking & Crill 1994, Bergman *et al* 1998,

Segers 1998). On the basis of previous research, the main artificial effects of either opaque or transparent chambers come from the 'long coverage period' (Morrissey *et al* 1993, Chanton & Whiting 1995). Here, we employed a portable greenhouse gas analyzer with a 1 Hz response rate, which allowed covering for a significantly shorter period (three minutes, compared to 30 min or longer for gas sampling and the Gas Chromatography method). We hypothesized that there could be a significant difference in CH<sub>4</sub> flux between opaque and transparent chambers as a result of the absence or presence of the photosynthesis process.

A group of opaque—transparent chamber pair measurements were conducted in a boreal peatland complex (including natural peatlands, drained peatlands, and discontinued pasture peatlands with drainage) throughout the growing season (May–October) of 2013. To cover as many vegetation or microtopography types as possible, different communities in the discontinued pasture (i.e., shrub dominated, grass dominated, and ditch) and microtopography (i.e., hummock, hollow, ditch, and pool) in the drained or undisturbed peatlands were covered separately and measured. Our specific objectives were: (1) to investigate the difference between opaque and transparent chambers for measuring CH<sub>4</sub> fluxes within a short covering period (three minutes); and (2) to identify if a similar phenomenon exists among different communities or hummocks and hollows in boreal peatlands.

## 2. Research sites and methods

### 2.1. Site description and experimental design

Our research sites are located in Robinsons pasture, western Newfoundland, 100 km southwest of Corner Brook, Newfoundland and Labrador (48° 15.842'N, 58° 39.913' W). It is an oceanic temperate climate with an annual rainfall of 1340 mm and yearly average temperatures of 5 °C, average January and July temperature of −9 ~ −2 °C and 13 ~ 20 °C respectively (1981–2010) (data from the nearest weather station in Stephenville, ~50 km away from our site). Our site is a peatland complex, comprising of a discontinued pasture, drained peatlands, and natural peatlands. The discontinued pasture was converted from drained peatland 35 years ago, and was abandoned after 10 years of active pasture. It is composed of patches of different dominant species, including reed canary grass (*Phalaris arundinacea*) dominated patches, various lower herbaceous and graminoid species (*Carex* spp., *Ranunculus acris*, *Ranunculus repens*, *Hieracium* sp.) dominated patches, and clumps of low shrubs overtopped by the tall grass, including sweet gale (*Myrica gale*), labrador tea (*Rhododendron groenlandicum*), mountain fly honeysuckle (*Lonicera villosa*), rhodora (*Rhododendron canadense*), and chokeberry (*Photinia* sp.), with a serious decline of *Sphagnum* moss compared to the natural and drained peatlands. The drained peatlands are with a substrate mostly of *Sphagnum* spp. (e.g., *S. Warnstorfii*, *S. capillifolium*) covered partly with several species of lichens (*Cladina* spp.). Patches of low ericaceous shrubs, such as huckleberries (*Gaylussacia* spp.),

are interspersed with a variety of other shrubs (*R. groenlandicum*) and herbs (*Trichophorum cespitosum*) typical of this type of peatland on the island of Newfoundland. The natural peatlands are wetter than the drained peatlands and include some wet depressions and peatland pools (permanently inundated with about 40–60 cm of standing water depth, from about 10–200 m<sup>2</sup> in area). The same *Sphagnum* moss covers the drier hummocks and many of the same ericaceous shrubs and herbs are also seen on the hummocks and hollows, but with more lush and vigorous growth. Microtopography, comprising of hummocks and hollows (dominated by sedges, with saturated surface peat as a result of the high water table level), exists in the natural peatlands and drained peatlands, but it disappeared in the discontinued pasture peatlands.

In the discontinued pasture, three plots were established, and in each plot four subplots were established to cover four communities, each of which has its dominated species, such as reed canary grass dominated, lower herbaceous and graminoid dominated, sweet gale and labrador tea dominated. One drainage ditch subplot was also established in each plot. Three plots were also established in the drained peatlands, and in each plot three subplots were established to cover one hummock, hollow, and drainage ditch. In the natural peatlands, three plots were set up, and in each plot three subplots were set up to cover one hummock, hollow, and pool.

## 2.2. Measurement of CO<sub>2</sub> and CH<sub>4</sub> fluxes

Boardwalks were constructed to prevent any disturbance to peat gas storage and emission during our measurements and to prevent any damage to the vegetation when regularly visiting the site. The PVC (polyvinyl chloride polymer) collars (26 cm in inner diameter) were permanently inserted into the peat to a depth of 10–15 cm of each subplot in early May, 2013 before the start of our measurements. The upper part of the collars had a groove for the water seal needed for the chamber measurements. Adjacent to each of the collars, perforated ABS (acrylonitrile butadiene styrene) pipes with sealed bottoms were inserted into the peat to measure water table depth. One permanent floating chamber frame with four ABS pipes was established in each pool, where a collar was not employed due to the self-seal characteristic of water. Our measurements were conducted biweekly or monthly from May to October in 2013.

CH<sub>4</sub> emissions and CO<sub>2</sub> exchange rates of each subplot were measured by an Ultra-Portable Greenhouse Gas Analyzer (Los Gatos Research, CA, USA) connected to a transparent chamber (made by a clear acrylic tube, which allows ~90% light transmission) or an opaque chamber (made by PVC tube covered by aluminum foil). All the measurements were made between 10:00 and 16:00 of the day. Both chambers were 50 cm in height and 26.3 cm in diameter. Air from the chambers passed through 4 m of tubing with an internal diameter of 3 mm to the analytical box. After the non-destructive analysis, it went back to the chambers. Concentrations of CH<sub>4</sub>, H<sub>2</sub>O, and CO<sub>2</sub> as well as the air temperature inside the chambers were recorded. There was a battery-operated fan in the chambers to help mix the air while

doing the measurement. The chambers were equipped with a capillary tube to retain atmospheric pressure inside the chambers when sampling.

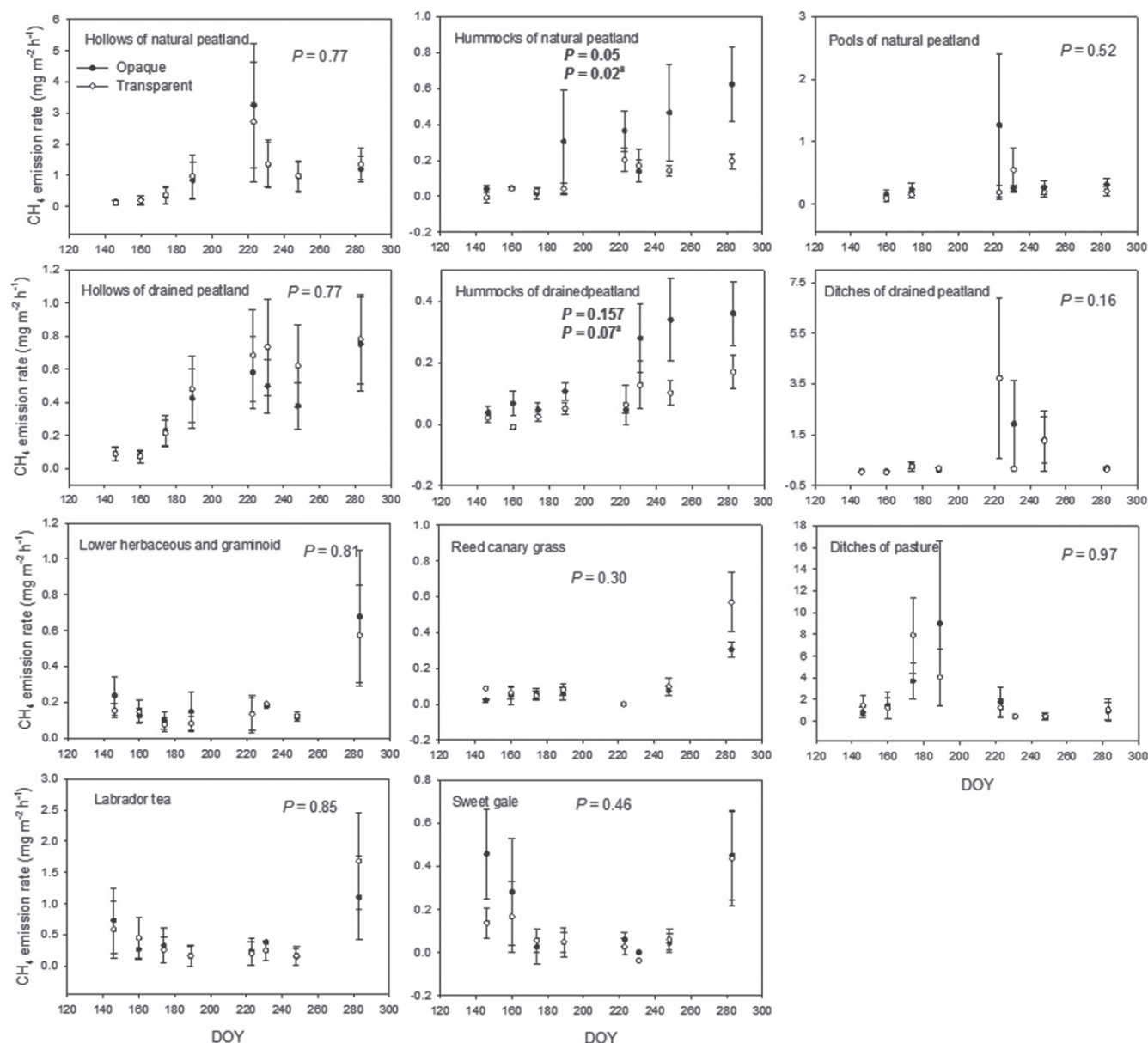
The gas concentration data were collected at 1 Hz rate and the data acquisition lasted for three minutes for both chambers. There was one to two minutes for the equilibrium between the opaque and transparent chamber measurements. We randomly chose either the transparent or the opaque chamber measurement as the first measurement for each subplot. All fluxes were adjusted for field sampling temperature, headspace volume, and chamber area (Holland *et al* 1999), and calculated from the slope of concentration change in the closed chamber (Mastepanov *et al* 2008). To remove the influence of increasing H<sub>2</sub>O in the chamber, the dry mixing ratio of CH<sub>4</sub> was calculated before calculating the slope of concentration change. The net ecosystem CO<sub>2</sub> exchange (NEE) and methane emission rate with light (CH<sub>4</sub> Transparent) were obtained by the transparent chamber measurements, and the total release of CO<sub>2</sub> (R<sub>ECO</sub>) and methane emission rate without light (CH<sub>4</sub> Opaque) were obtained by the opaque chamber measurements. Soil temperatures were measured near the collars with a temperature probe at the depths of 5 cm and 20 cm when the gas flux measurement was taken. The water table was measured from the perforated pipes with a ruler. Soil moisture at 0–5 cm was measured with a GS3 probe connected to a ProCheck reader (Decagon Devices).

## 2.3. Gross photosynthesis rate and the difference in CH<sub>4</sub> emission between the opaque and transparent chambers

Negative NEE values were used when the CO<sub>2</sub> fixation by the vegetation exceeded the total respiration of the vegetation and the soil. With this approach, respiration had positive values. Similarly, the CH<sub>4</sub> emissions were positive, and an uptake from the atmosphere to the soil had negative values. The gross photosynthesis (P<sub>G</sub>) is the result of subtracting R<sub>ECO</sub> from NEE, i.e.,  $P_G = NEE - R_{ECO}$ . The R<sub>ECO</sub> was the sum of CO<sub>2</sub> produced by plant dark respiration, and by respiration of microbes and soil fauna (Nykänen *et al* 2003). We defined the artificial bias in the CH<sub>4</sub> emission rate of the transparent chamber compared with the opaque chamber as the difference in CH<sub>4</sub> fluxes obtained by the opaque versus the transparent chamber, i.e.,  $CH_4 \text{ Diff.} = CH_4 \text{ Opaque} - CH_4 \text{ Transparent}$ . The accumulated CH<sub>4</sub> emissions across the growing season were simply calculated by the integration on the emission rate and the growing season period.

## 2.4. Data analysis

Repeated measures of GLMs (generalized linear model) were used to evaluate the effects of the chamber (opaque versus transparent) on CH<sub>4</sub> flux, air temperature inside the chamber across the growing season. Linear regressions were conducted to investigate the correlations between the P<sub>G</sub> and CH<sub>4</sub> Diff. rate, the CO<sub>2</sub> and CH<sub>4</sub> flux, and to examine the correlations between soil water content, water table depth, and the CH<sub>4</sub> emission rate. Data analysis was conducted by IBM SPSS 20.



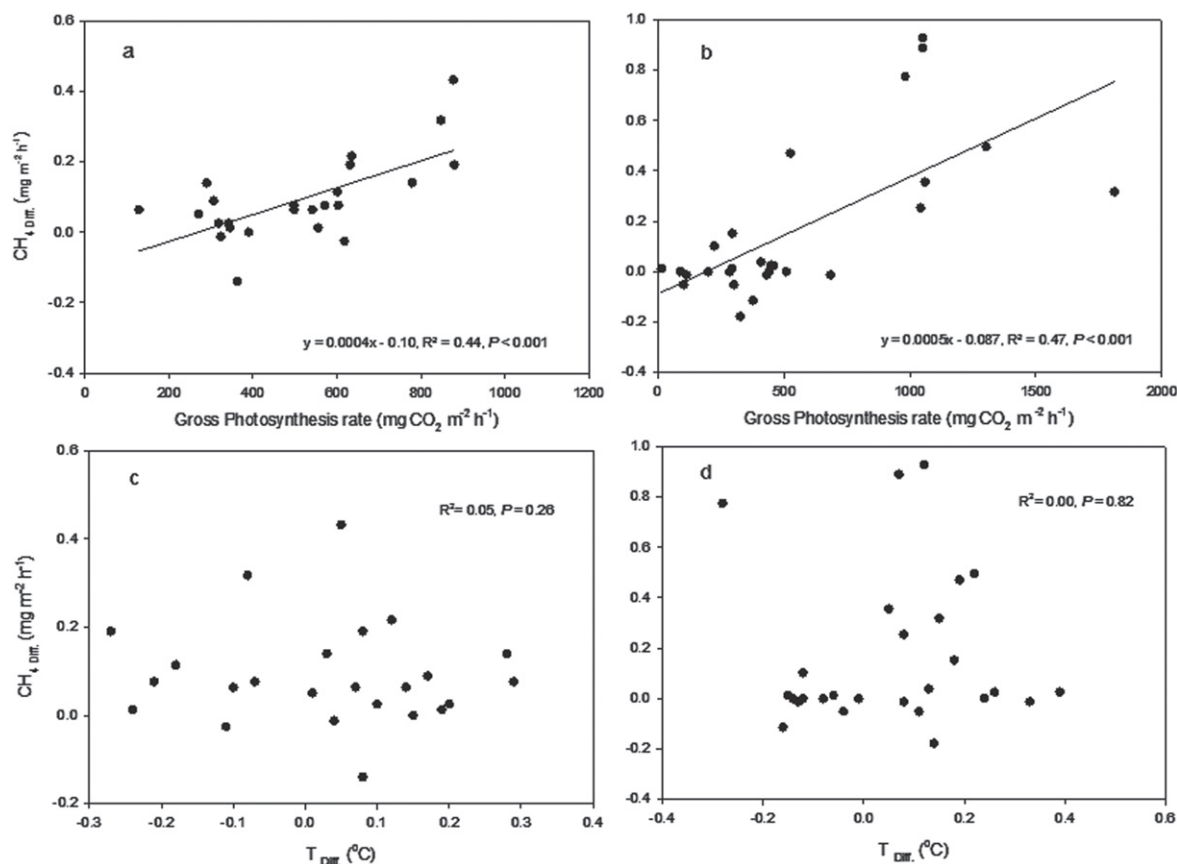
**Figure 1.** Emission patterns of the  $\text{CH}_4$  fluxes estimated with the opaque and transparent chambers in different sites, error bars denote standard errors of the mean ( $n=3$ ). <sup>a</sup> The  $P$  values are the result of ANOVA analysis.

### 3. Results

Significantly higher  $\text{CH}_4$  fluxes were measured with the opaque chambers compared to the transparent ones at the hummocks of both natural and drained peatlands (figure 1). At the hummocks of drained peatlands, the opaque chambers estimated a net emission of  $0.58 \pm 0.16$  (SE)  $\text{g CH}_4 \text{ m}^{-2}$  across the growing season, while the transparent chambers showed a net emission of  $0.24 \pm 0.10 \text{ g CH}_4 \text{ m}^{-2}$  (table 1). At the hummocks of the natural peatlands, the opaque chambers estimated  $0.78 \pm 0.23 \text{ g CH}_4 \text{ m}^{-2}$ , which was a 3.25 times higher methane emission compared with the transparent chambers ( $0.24 \pm 0.07 \text{ g m}^{-2}$ ) across the growing season (table 1). No significant difference in  $\text{CH}_4$  fluxes between the opaque and transparent chambers was found for other sites (figure 1 and table 1).

We did not find any significant difference in air temperature between the transparent and opaque chambers during the three minutes of measurement period ( $P > 0.05$ ) across the growing season (figure 5). Significantly positive relationships between  $P_G$  and the difference in  $\text{CH}_4$  obtained between the opaque versus the transparent chambers were found at the hummocks of both natural and drained peatlands (figures 2(a), (b)). The  $P_G$  accounted for approximately 44–47% seasonal variation in ‘artificial bias’ between opaque versus transparent chambers (figures 2(a), (b)). No correlation was found between the difference in air temperature and  $\text{CH}_4$  flux obtained by opaque versus transparent chambers (figures 2(c), (d)). Significantly negative correlations between NEE and  $\text{CH}_4$  Transparent (figures 3(a), (c)), while positive correlations between  $R_{\text{ECO}}$  and  $\text{CH}_4$  Opaque (figures 3(b), (d)), were found at hummocks for both drained and natural peatlands. Both soil





**Figure 2.** Relationships between the gross photosynthesis rate and the difference in methane flux obtained by the opaque versus transparent chambers ( $\text{CH}_4 \text{ Diff.}$ ) at the hummocks in drained (a) and natural (b) peatlands. Relationships between air temperature difference ( $T_{\text{Diff.}} = T_{\text{Transparent}} - T_{\text{Opaque}}$ ) inside the chamber and the  $\text{CH}_4 \text{ Diff.}$  at the hummocks in drained (c) and natural (d) peatlands.

**Table 1.** Estimated growing season (May–October 2013)  $\text{CH}_4$  emissions with the transparent and opaque chambers.

Types	Transparent chamber ( $\text{g CH}_4 \text{ m}^{-2}$ )	Opaque chamber ( $\text{g CH}_4 \text{ m}^{-2}$ )
Natural peatlands	—	—
Hollows	1.93 (1.32)	2.51 (1.95)
Hummocks	0.24 (0.07)	0.78 (0.23) <sup>a</sup>
Pools	0.63 (0.19)	1.43 (0.98)
Drained peatlands	—	—
Hollows	1.67 (0.66)	1.36 (0.51)
Hummocks	0.24 (0.10)	0.58 (0.16) <sup>b</sup>
Ditches	2.95 (2.31)	18.48 (9.23)
Discontinued pasture	—	—
Reed canary grass	0.46 (0.13)	0.26 (0.06)
Lower herbaceous and graminoid	0.56 (0.25)	0.66 (0.25)
Shrub a (Labrador tea)	1.40 (0.84)	1.13 (0.83)
Shrub b (Sweet gale)	0.36 (0.24)	0.47 (0.24)
Ditches	7.41 (4.17)	9.03 (6.95)

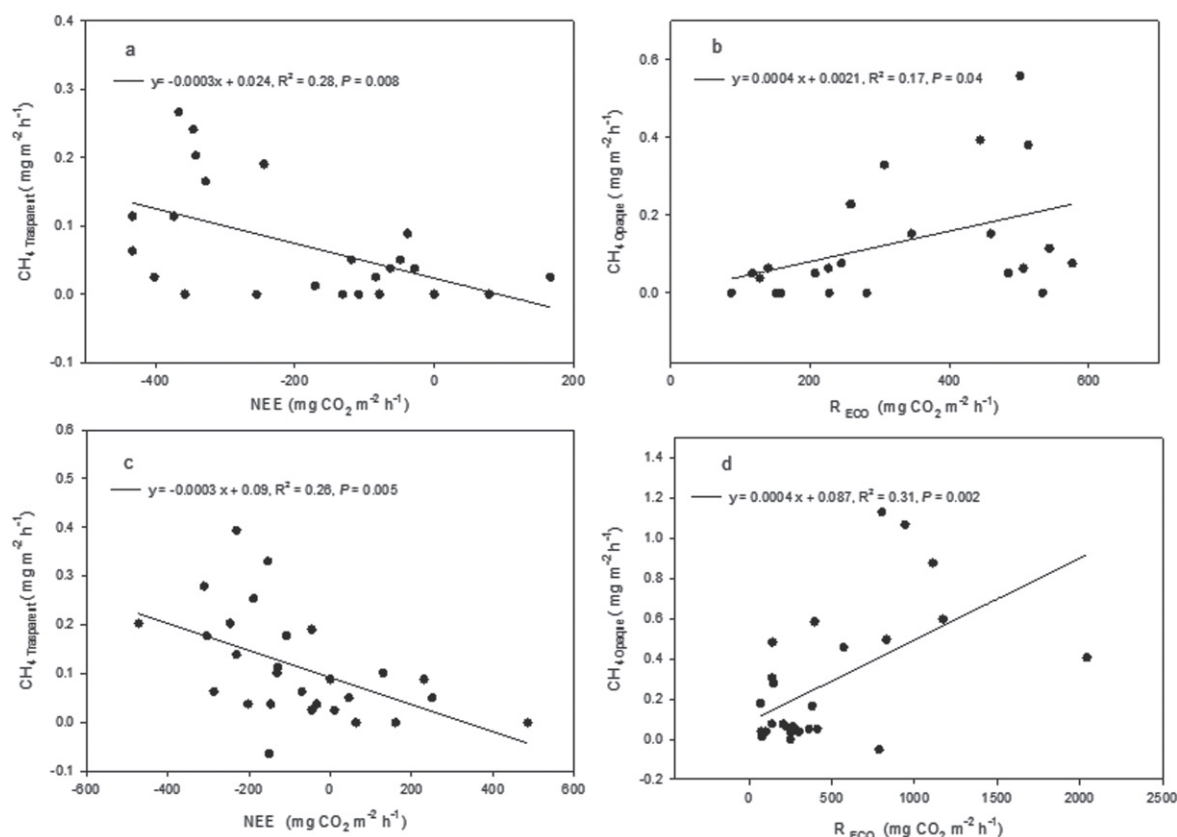
<sup>a</sup> Denote paired *t*-test (2-tailed)  $P=0.08$ .

<sup>b</sup> Denote paired *t*-test (2-tailed)  $P=0.047$ .

moisture and water table depth accounted for the spatial variations of the  $\text{CH}_4$  fluxes among sites across the growing season (table 2).

#### 4. Discussion

Significantly higher methane fluxes were found by the opaque chambers compared with the transparent chambers at the hummocks in both the drained and the natural peatlands (figure 1, table 1). However, no significant difference was found in  $\text{CH}_4$  fluxes between the transparent and opaque chambers at other subplots. Livingston and Hutchinson (1995) recommended a minimization of the headspace heating as a precautionary measure against the unknown bias because the temperature in the chamber headspace may increase significantly during the closed chamber measurements at high irradiances (Günther *et al* 2013). However, we did not find any significant difference in the air temperature between the chambers (figure 5), because we only closed the chambers for three minutes during our measurements. This evidence makes us speculate that any difference in  $\text{CH}_4$  emission rate between the opaque and transparent chambers, if detected, was not attributed to the temperature difference. No correlation between the difference in air temperature and the difference in  $\text{CH}_4$  flux obtained by the opaque versus



**Figure 3.** Relationships between the net ecosystem CO<sub>2</sub> exchange (NEE, negative value means net uptake of CO<sub>2</sub>) and the methane flux obtained by the transparent chamber (CH<sub>4</sub> Transparent) at the hummocks in drained (a) and natural (c) peatlands. Relationships between ecosystem respiration (R<sub>ECO</sub>) and the methane flux obtained by the opaque chamber (CH<sub>4</sub> Opaque) at the hummocks in drained (b) and natural (d) peatlands.

**Table 2.** Correlations between the CH<sub>4</sub> emission rate (estimated with the transparent chamber) and soil moisture at 0–5 cm, or water table depth throughout our sites during each measurement campaign<sup>a</sup>.

Date	Soil moisture of 0–5 cm			Water table depth		
	<i>R</i>	<i>P</i> value	<i>n</i>	<i>R</i>	<i>P</i> value	<i>n</i>
27 May	0.57	0.006	22	0.46	0.021	25
10 June	0.45	0.03	23	0.44	0.021	26
24 June	0.513	0.006	27	0.637	<0.001	27
9 July	0.59	0.002	25	0.63	0.001	25
12 August	N	N	N	0.56	0.002	29
20 August	N	N	N	0.56	0.016	18
6 September	0.509	0.005	29	0.474	0.009	29
11 October	0.553	0.002	29	0.399	0.032	29

<sup>a</sup> Data from the pools and ditches of drained peatlands were excluded in our analysis because soil moisture was not determined. N: not determined (soil moisture sensor failed).

transparent chambers (figures 2(c), (d)) confirmed our speculation. However, our regression analysis, where the gross photosynthesis rate positively correlated with the difference in CH<sub>4</sub> flux obtained by the opaque versus transparent chambers at the hummocks in both the drained and the natural peatlands (figures 2(a), (b)), implied that the photosynthesis process can explain the ‘artificial bias’ (the opaque versus transparent, explained 44–47% of this ‘artificial bias’, figures 2(a), (b)) in CH<sub>4</sub> estimation based on the enclosure method on the hummocks. In our study sites, water table depths were lower than

10 cm below ground (excluding ditches and pools) (figure 4). We can consider the 0–10 cm depth of peat as the potential oxidation layer because the aerobic layer is defined by the water table position (Bubier & Moore 1994, Frohling *et al* 2002). With water tables being at or near the surface, the *Sphagnum* moss layer represents most of the aerobic environment where CH<sub>4</sub> oxidation can occur (Basiliko *et al* 2004), particularly at the hummocks, where CH<sub>4</sub> has to transport through it before being released into the atmosphere. Thus, oxygen derived from photosynthesis can be more important

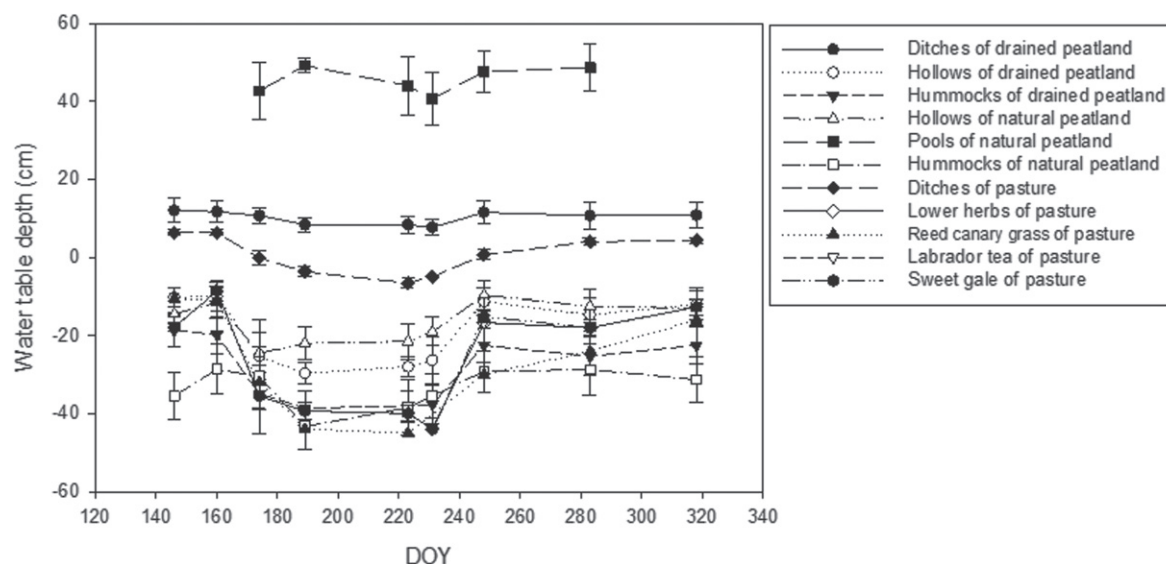


Figure 4. Seasonal patterns of water table depth at different sites.

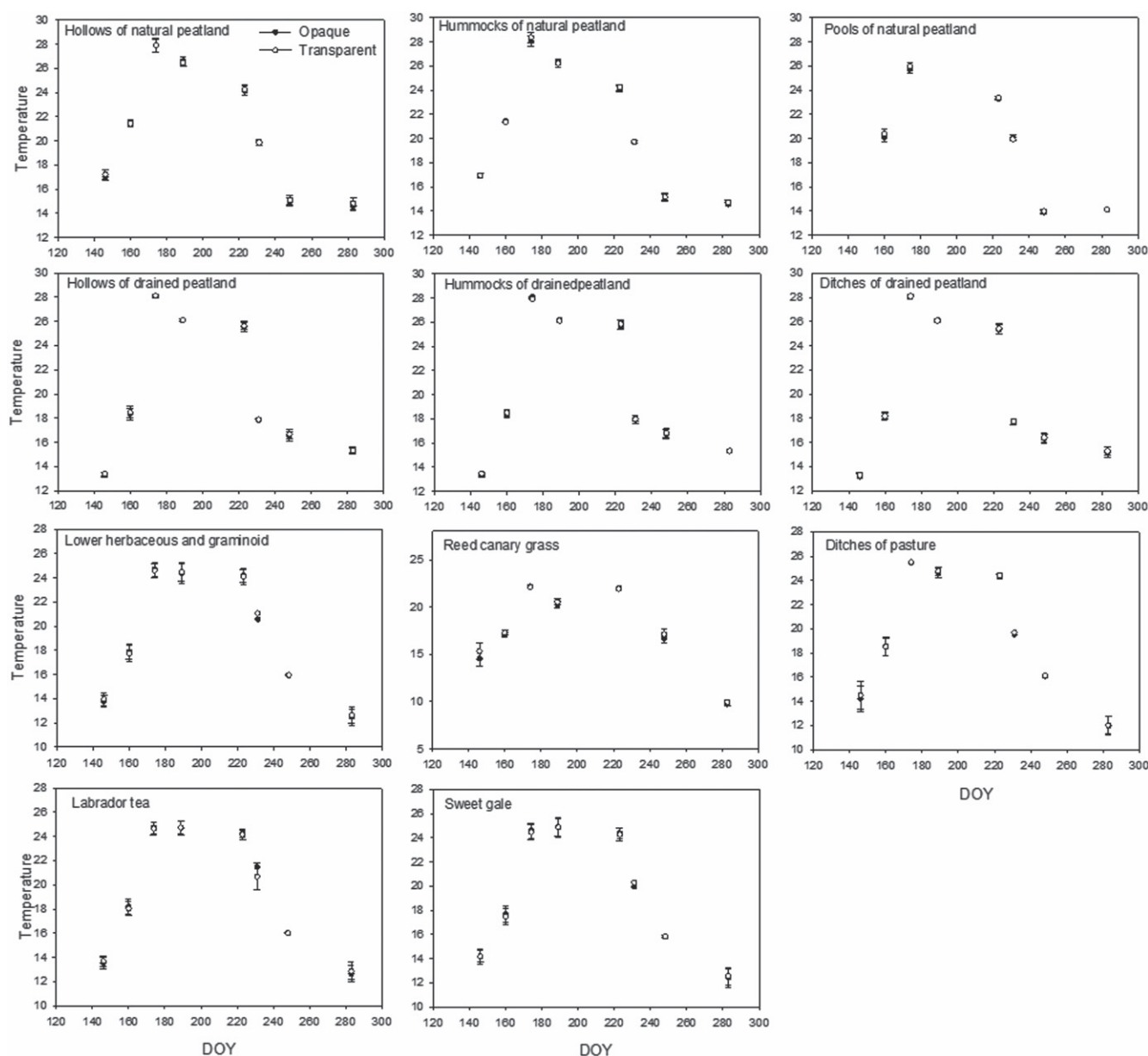
for  $\text{CH}_4$  oxidation in this layer. On the other hand, the symbiotic relationship between methanotrophs and *Sphagnum* mosses, which was reported to facilitate recycling of the oxygen produced from photosynthesis and  $\text{CH}_4$  derived from decaying plants (Raghoebarsing *et al* 2005, Kip *et al* 2010), might also be contributing to the connection between photosynthesis and ‘artificial bias’. The significantly negative relationships between NEE and  $\text{CH}_4$  Transparent (figures 3(a), (c)), as well as the significantly positive relationships between  $R_{\text{ECO}}$  and  $\text{CH}_4$  Opaque (figures 3(b), (d)), both imply the connections between  $\text{CO}_2$  and  $\text{CH}_4$  fluxes, and partly support our speculation on the connection between photosynthesis process and the  $\text{CH}_4$  oxidation. Apparently, the mechanisms underlying the photosynthesis process and the ‘artificial bias’ of  $\text{CH}_4$  flux estimation, however, need to be further elucidated through a process-based research, such as the stable isotope (e.g.,  $^{13}\text{C}$ ) labeling.

The significant differences in  $\text{CH}_4$  emission rate between the transparent and opaque chambers were only found at the hummocks rather than the hollows. One of the reasons might be that the high moisture content in the surface soil at the hollows, as a result of high water table levels, significantly reduces the ability of the oxidation potential. Larmola *et al* (2009) found that water level was the key environmental factor regulating methanotrophy in *Sphagnum* moss layer. Therefore, the  $\text{CH}_4$  will bypass the oxidation process and become released directly to the atmosphere, which leads to no significant differences in the  $\text{CH}_4$  emission between the transparent and opaque chambers. Another reason might be the dominance of sedges at the hollows in our study sites, because sedges can help emit more  $\text{CH}_4$  (Dorodnikov *et al* 2011, Olefeldt *et al* 2013), especially during the presence of light when the stomata are open. It was also reported that stomata significantly controlled methane release from wetlands (Morrissey *et al* 1993). Thus,  $\text{CH}_4$  emission facilitated by plants offset the lowered  $\text{CH}_4$  emission due to oxidation

and did not result in significantly lower  $\text{CH}_4$  flux measured by transparent chambers at hollows. No significant difference here in the pasture might be simply attributed to the serious decline of *Sphagnum* moss in these sites. A closed chamber method has a number of well-known limitations and artifacts in estimating the  $\text{CH}_4$  flux (Morrissey *et al* 1993, Frohling & Crill 1994, Chanton & Whiting 1995). Our results suggest that the artificial properties of a chamber (transparency/opacity) can be vitally important in some cases (i.e., hummocks), but negligible in others, even during a significantly shorter closure period (three minutes).

We found that not only the water table depths, but also the soil moisture of the 0–5 cm, showed a significant correlation with the  $\text{CH}_4$  emission rates across our sites (table 2). This result indicates that the potential oxidation layer plays an important role in regulating the  $\text{CH}_4$  transportation in our sites. Our results might be able to help explain the recent study that reported greater nighttime  $\text{CH}_4$  emissions than those recorded during the daytime in a fen with a hummock-hollow microtopography (Godwin *et al* 2013). Clearly, our results indicate that the opaque chambers estimated a higher  $\text{CH}_4$  flux than the transparent ones at the hummocks, which is a typical setting of microtopography in boreal peatlands (Bubier *et al* 1993). In contrast, Günther *et al* (2013) found that the fluxes measured by the transparent chamber almost doubled those measured by the opaque chambers in the convective transporting *Phragmites* stand as a result of internal convective gas transport responding quickly to changes in irradiation. Shrubs and sedges apparently play a significantly different role than *Sphagnum* moss in regulating the  $\text{CH}_4$  emissions under the ambient light. Our findings suggest that the difference in the chamber method will possibly give us significantly different  $\text{CH}_4$  flux, and thus increase the uncertainties in the  $\text{CH}_4$  flux estimation. We propose that the differences in the microtopography (Wu *et al* 2011) and the corresponding vegetation need to be





**Figure 5.** Seasonal patterns of the air temperatures ( $^{\circ}\text{C}$ ) inside the opaque and transparent chambers in different sites; error bars denote standard errors of the mean ( $n=3$ ).

considered when modeling the methane transportation in a peatland. Our results also suggest that the surface soil water content plays an important role in regulating the methane emissions in these peatlands, and therefore not only water table depth but also the surface soil moisture needs to be monitored to assist in interpreting the  $\text{CH}_4$  flux. The magnitude of our fluxes is consistent with what is presented in the literature (Waddington & Roulet 1996, Bubier *et al* 2005, Forbrich *et al* 2011) where the hummocks are at the lower end of the methane flux range, where the hollows and minerotrophic peatlands are the main source of  $\text{CH}_4$  to the atmosphere at the ecosystem scale. It is critical to address that the larger fluxes measured with the opaque chamber are still relatively low compared to the fluxes from the other microforms in this study (figure 1). Therefore, the variability of

$\text{CH}_4$  fluxes observed between the two chamber types would not have a significant impact on the ecosystem-scale estimation of the  $\text{CH}_4$  budget.

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