



## RESEARCH ARTICLE

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## Special Section:

Development of Isotopic  
Proxies for Paleoenvironmental  
Interpretation: A Carbon  
Perspective (DIPPI-C)

## Key Points:

- D/H and  $^{13}\text{C}/^{12}\text{C}$  ratios of leaf waxes constrain proportion recycled methane in *Sphagnum*
- High water table supports increased *Sphagnum* methane recycling
- Methane transport through sedge aerenchyma inhibits methane recycling

## Supporting Information:

- Appendix Table 1
- Readme
- R script

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## A novel framework for quantifying past methane recycling by *Sphagnum*-methanotroph symbiosis using carbon and hydrogen isotope ratios of leaf wax biomarkers

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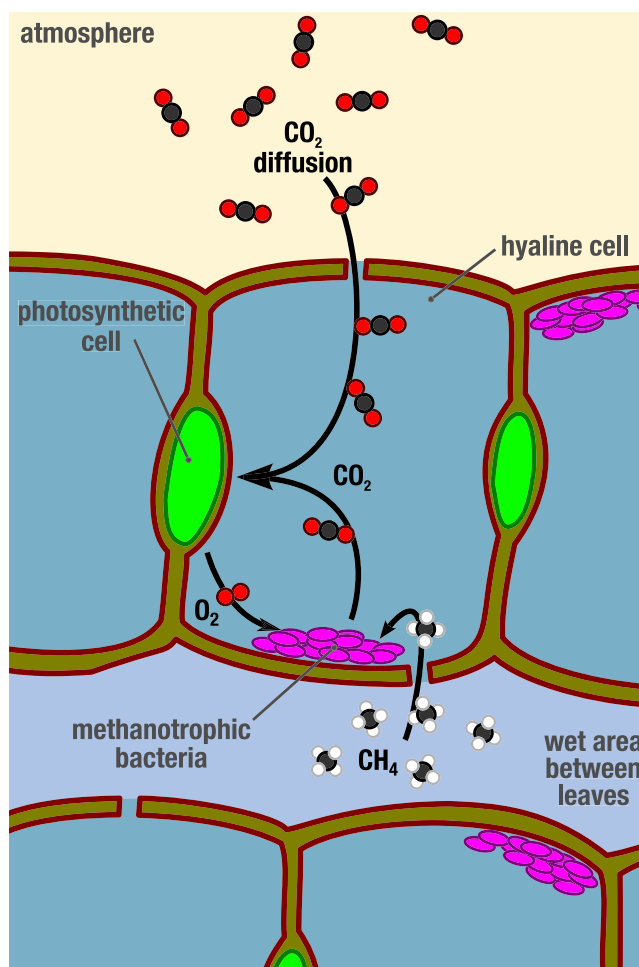
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**Abstract** The concentration of atmospheric methane is strongly linked to variations in Earth's climate. Currently, we can directly reconstruct the total atmospheric concentration of methane, but not individual terms of the methane cycle. Northern wetlands, dominated by *Sphagnum*, are an important contributor of atmospheric methane, and we seek to understand the methane cycle in these systems. We present a novel method for quantifying the proportion of carbon *Sphagnum* assimilates from its methanotrophic symbionts using stable isotope ratios of leaf-wax biomarkers. Carbon isotope ratios of *Sphagnum* compounds are determined by two competing influences, water content and the isotope ratio of source carbon. We disentangled these effects using a combined hydrogen and carbon isotope approach. We constrained *Sphagnum* water content using the contrast between the hydrogen isotope ratios of *Sphagnum* and vascular plant biomarkers. We then used *Sphagnum* water content to calculate the carbon isotope ratio of *Sphagnum*'s carbon pool. Using a mass balance equation, we calculated the proportion of recycled methane contributed to the *Sphagnum* carbon pool, "PRM." We quantified PRM in peat monoliths from three microhabitats in the Mer Bleue peatland complex. Modern studies have shown that water table depth and vegetation have strong influences on the peatland methane cycle on instrumental time scales. With this new approach,  $\delta^{13}\text{C}$  of *Sphagnum* compounds are now a useful tool for investigating the relationships among hydrology, vegetation, and methanotrophy in *Sphagnum* peatlands over the time scales of entire peatland sediment records, vital to our understanding of the global carbon cycle through the Late Glacial and Holocene.

### 1. Introduction

Atmospheric concentrations of methane, an important greenhouse gas, have changed dramatically over the late glacial and Holocene. While these changes in concentration are well constrained by samples from ice cores, the reasons for the observed changes remain in the realm of hypothesis. Several lines of evidence have emerged from studies of methane in ice cores implicating northern peatlands as an important methane source, including higher concentrations of methane in the northern hemisphere relative to the southern hemisphere, indicating a northern source [Chappellaz *et al.*, 1997; Dallenbach *et al.*, 2000], and depleted H and C isotope ratios of atmospheric methane in the Holocene relative to the glacial, indicating a biogenic, wetland source [Möller *et al.*, 2013]. Other studies of peatland sediments have attempted to address the atmospheric methane source question by synthesizing peatland initiation ages or peatland ecological changes through time and comparing these to the changes in methane concentration in ice [Macdonald *et al.*, 2006; Korhola *et al.*, 2010; Yu *et al.*, 2013]. While it seems likely that peatland dynamics are responsible for much of the variability of atmospheric methane, all of this evidence is fundamentally circumstantial, and no study has directly measured any part of the peatland methane cycle over the Holocene or late glacial. We present here a novel method for reconstructing one part of the peatland methane cycle—the proportion of methane recycled by methanotroph/*Sphagnum* symbiosis—using the carbon and hydrogen isotope ratios of sedimentary biomarkers in northern peatlands. While it is difficult to directly connect this parameter to methane flux to the atmosphere, it is an important part of the peatland methane cycle that has not previously been quantified.

The methane cycle has been directly measured in modern peatlands, and although emissions from peatlands account for about 10% of atmospheric methane today [Bridgman *et al.*, 2006], it has also been observed that these peatlands do not emit nearly as much methane as is produced at depth [Hornibrook *et al.*, 2009]. This apparent loss of methane has been ascribed to bacterially mediated oxidation in the upper



**Figure 1.** Schematic diagram illustrating the two sources of carbon for *Sphagnum magellanicum*. CO<sub>2</sub> from the atmosphere must diffuse through water in the hyaline cells before reaching the photosynthetic cells. Oxygen from *Sphagnum* photosynthesis is used by the methanotrophs to respire methane, and the resulting CO<sub>2</sub> is in turn used by *Sphagnum*.

control on the peatland methane cycle [Blodau, 2002; Roulet et al., 2007]. While peatlands are, in general, saturated, anoxic, acidic environments, hydrologic balance does vary, creating conditions that are more or less favorable for methanogenesis or methanotrophy. The surface of a peatland is also heterogeneous, and the typical “hummock and hollow” microtopography produces locations within a peatland where the water table depth can be as different as 60 cm [Booth, 2002]. During times or in locations where the water table is high, anoxic conditions are allowed to fully develop and persist in the peat, fostering an active methanogenic community. Methanotrophy is also found to be most active in locations where the water table is close to or at the surface of the peat [Basiliko et al., 2004; Raghoebarsing et al., 2005; Kip et al., 2010; Larmola et al., 2010]. Based on these observations, we expect that *Sphagnum*-methanotroph symbiosis should be most efficient under high water table conditions.

The vegetational composition at the peatland surface also has a strong influence on the methane cycle. Measurements of methane flux from peatlands in North America and Europe have shown that areas with abundant *Sphagnum* have much lower rates of methane flux than areas with abundant sedges (*Cyperaceae*). Sedges have aerenchyma, spongy tissue that transports oxygen from the atmosphere to the roots. These structures also allow methane produced in the rooting zone of these plants to escape to the atmosphere before it is oxidized by methanotrophic bacteria [Segers, 1998; Frenzel and Karofeld, 2000; Laanbroek, 2010]. We therefore expect that *Sphagnum* living amongst abundant sedges will have a lower proportion of carbon from recycled methane as *Sphagnum* without nearby sedges.

layers of peat. The bacteria responsible for this consumption of methane have been found to be symbiotic with *Sphagnum*; methanotrophic bacteria reside inside the hyaline (water-holding) cells of *Sphagnum*, which uses the CO<sub>2</sub> produced by methane oxidation for photosynthesis [Raghoebarsing et al., 2005; Kip et al., 2010; Larmola et al., 2010]. The resulting O<sub>2</sub> from *Sphagnum* photosynthesis is used by the methanotrophs to oxidize methane (Figure 1). For modern peatlands, recent investigations have begun to constrain with increasing detail the relationships among vegetation type, hydrology, methane flux, and the activity of *Sphagnum*-methanotroph symbiosis [Chen et al., 2008; Kip et al., 2010]. These studies are limited, however, to the instrumental period. No proxy for any part of the peatland methane cycle currently exists for testing the applicability of uniformitarianism to the relationships we observe in the modern, or for tracking changes in the methane cycle of the past.

The depth of the water table, or, correspondingly, the size of the aerated zone, exerts a strong

Promise for a methane cycle paleo-proxy lies in the carbon isotope ratios of *Sphagnum*. Because biogenic methane, such as that produced in peatlands, has a distinctly more negative carbon isotope ratio, the CO<sub>2</sub> that results from the oxidation of that methane also has a distinct carbon isotope ratio. *Sphagnum* using this CO<sub>2</sub> for photosynthesis should have a significantly more negative carbon isotope ratio than a typical C3 plant. Indeed, *Sphagnum* has been found to have a light carbon isotope signature for bulk plant material as well as individual compounds, particularly leaf waxes. Here as in previous work, tricosane is used as an effective biomarker for *Sphagnum* in peatland sediment [Baas *et al.*, 2000; Nott *et al.*, 2000; Pancost *et al.*, 2002; Xie *et al.*, 2004; Nichols *et al.*, 2006; Bush and McInerney, 2013]. Confounding this carbon isotope approach, however, is the fact that moisture content strongly affects the carbon isotope ratio of *Sphagnum* in addition to the isotope ratio of the source carbon [Williams and Flanagan, 1996]. Here we disentangle these two effects using a combined hydrogen and carbon isotope approach.

We present a method for quantifying past changes in the proportion of carbon in *Sphagnum* coming from recycled methane by independently constraining the water content of *Sphagnum* using a hydrogen isotope method. *Sphagnum* has no vascular system, and thus can only get water by capillary action from the top ~20 cm of the peatland, which has an isotope ratio strongly affected by evaporation. Vascular plants have roots that can obtain water from below the surface that is not affected by evaporation [Nichols *et al.*, 2010]. Therefore, the contrast in  $\delta D$  between *Sphagnum* and vascular plant biomarkers can be used to estimate evaporative water loss from within and between *Sphagnum* leaves—approximately equivalent to *Sphagnum* water content [Nichols *et al.*, 2010]. *Sphagnum*'s carbon isotope discrimination from CO<sub>2</sub> to biomass is related to water content by an experimentally derived function. Thus, we can use hydrogen isotope ratios of biomarkers to derive the carbon isotope ratio of the carbon dioxide used by *Sphagnum*. We then use a mass balance equation and the distinctive  $\delta^{13}C$  of methane derived and atmospheric CO<sub>2</sub> to find the proportion of each used by *Sphagnum*.

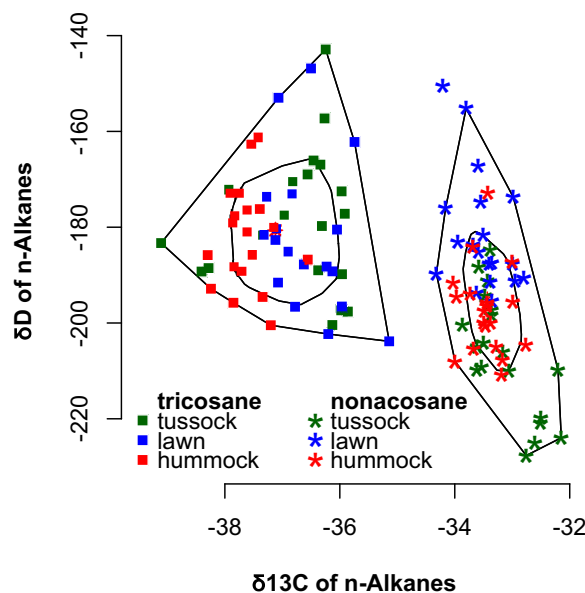
We applied our new method to short cores from three different sites within the Mer Bleue peatland complex near Ottawa, ON, Canada. Scores of studies have been performed at this site, including measurements of methane flux [Moore *et al.*, 2011]. We chose a site at a *Sphagnum capillifolium*-dominated lawn with a higher water table (the "Lawn" site), a *Sphagnum magellanicum*-dominated site with a lower water table (the "Hummock" site), and an *Eriophorum vaginatum* and *Sphagnum capillifolium*-dominated site with variable water table dynamics (the "Tussock" site). Each of the three sites is located adjacent to long-term methane flux measurement sites. We chose these sites to be able to test the influence of both water table and vegetation on *Sphagnum*-methanotroph symbiosis.

## 2. Methods

A peat monolith was sampled from each of the three target locations, the *Sphagnum capillifolium* lawn, the *Sphagnum magellanicum* hummock, and the *Eriophorum vaginatum* tussock. Twenty contiguous, 1 cm thick peat samples were cut from each monolith. Extraction and purification of *n*-alkanes from peat samples was performed according to previously described methods [Nichols *et al.*, 2010]. Briefly, peat samples were freeze-dried, and lipids were extracted with hexane by ultrasonic agitation. Total lipid extracts were separated over a silica gel flash column. *n*-Alkanes elute with hexane and were quantified by gas chromatography-flame ionization detection (GC-FID). Carbon and hydrogen isotope ratios of *n*-alkanes were measured by gas chromatography-continuous flow isotope ratio mass spectrometry. Carbon isotopes were measured at the Woods Hole Oceanographic Institution Organic Mass Spectrometry Facility. Compounds eluting from the GC are oxidized to CO<sub>2</sub> at 1000°C in an alumina oxidation reactor with copper-nickel wire catalyst. Hydrogen isotope measurements were made at the Lamont Doherty Earth Observatory Biogeochemistry Laboratory on a Thermo DeltaV coupled to a Thermo Trace GC through a Thermo IsoLink and ConFlo IV. Eluting compounds were pyrolyzed to hydrogen gas at 1420°C in an empty alumina reactor. Evolved gases are introduced to the IRMS through a continuous flow device, and isotope ratios are calculated using a calibrated laboratory reference gas. Standard deviations of D/H measurements are <2‰ based on long-term repeat analyses of a lipid standard or <1.5‰ based on triplicate analysis of a single sample. H<sub>3</sub><sup>+</sup> factor during analysis of Mer Bleue samples remained consistently at 4.6.

## 3. Results and Discussion

We measured the stable hydrogen and carbon isotope ratios of tricosane and nonacosane from 20 contiguous 1 cm samples from each monolith. The clear separation between the two compounds in isotope space



**Figure 2.** Bagplots of isotope ratio measurements from *n*-alkanes at three sites in Mer Bleue Bog. A bagplot is a two-variable variation of a box-and-whisker plot. The inner polygon (the “bag”) for each data group circumscribes the *n*/2 datapoints closest to the two-variable median, while the outer polygon (the “loop”) circumscribes all the points that fall within the “fence” which is a polygon three times larger than the “bag.” Points outside the “loop” are considered outliers [Rousseeuw et al., 1999].

(Figure 2) reflects their different source plants, reinforcing the utility of tricosane and nonacosane as biomarkers for *Sphagnum* and vascular plants, respectively. Most distinctive is the complete separation on the carbon isotope scale. Tricosane is consistently depleted relative to nonacosane by 3–4‰. This depletion supports the hypothesis that *Sphagnum* carbon isotope ratios are strongly influenced by respired methane.

The interpretation of carbon isotope ratios of *Sphagnum* compounds in peatland surface samples and peat sediments has confounded researchers in the past [e.g., Xie et al., 2004], due to the competing influences of carbon source and moisture-controlled isotope discrimination [Markel et al., 2010]. Although laboratory experiments have shown a clear relationship between *Sphagnum* moisture content and carbon isotope discrimination [Williams and Flanagan, 1996], this relationship is much less clear in real peatland environments [Loisel et al., 2009; Markel et al., 2010]. The impact on *Sphagnum* δ<sup>13</sup>C of CO<sub>2</sub> from methane respired by symbiotic methanotrophic bacteria is, however, clear from some laboratory experiments and field studies [Nichols et al., 2009; Kip et al., 2010]. In order for carbon isotope ratios of *Sphagnum* compounds to be a useful paleoenvironmental tool, we must separate the effects of methanotrophy and water content.

To use our carbon isotope ratio measurements to constrain the contribution of respired methane to *Sphagnum*, we independently constrain the water content of *Sphagnum* using hydrogen isotopes. This method has been described and discussed previously [Nichols et al., 2010]. Because *Sphagnum* has no vascular system for water transport, it accesses water only by capillary action, and therefore uses water only from approximately the upper 20 cm of the peatland. This water is highly susceptible to evaporation, which strongly enriches the hydrogen isotope ratios of *Sphagnum* water. As water evaporates from inside and among the leaves of the *Sphagnum* (i.e., water content decreases), the hyaline cells of the *Sphagnum* and the surface of the peatland itself shrink as water is removed to the atmosphere [Clymo and Hayward, 1982; Kim and Verma, 1996], providing a progressively more enriched pool of water for *Sphagnum* to use [Nichols et al., 2010]. This evaporation signal is transferred to *Sphagnum* biomarkers (e.g., tricosane). Vascular plants, however, use water found deeper in the acrotelm, which is protected from evaporation by the shrinking peatland surface [Kim and Verma, 1996]. Thus, the δD signature of vascular plant biomarkers (e.g., nonacosane) is not affected by what in other terrestrial environments would be called soil water evaporation. With the δD of *Sphagnum* and vascular plant biomarkers, the fraction of water evaporated—essentially the *Sphagnum* water content—can be calculated using a Rayleigh evaporation model (equation (1)). The term, *f*, is the fraction of water remaining in *Sphagnum* after evaporation, or the fractional water content of *Sphagnum*. This value is calculated by comparing the δD of *Sphagnum*’s water with the δD of the water used by vascular plants [Nichols et al., 2010].

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$$\frac{\delta D_a - \delta D_s}{\epsilon_k - \epsilon^*} = \ln f \quad (1)$$

$$\varepsilon_{\text{vasc}} + \left( \frac{\varepsilon_{\text{vasc}} \times \delta D_{C_{29}}}{1000} \right) + \delta D_{C_{29}} = \delta D_a \quad (2)$$

$$\varepsilon_{\text{sph}} + \left( \frac{\varepsilon_{\text{sph}} \times \delta D_{C_{23}}}{1000} \right) + \delta D_{C_{23}} = \delta D_s \quad (3)$$

where

$\delta D_a$  = acrotelm water

$\delta D_s$  = Sphagnum water

$\varepsilon_k$  = kinetic fractionation factor

$\varepsilon^*$  = equilibrium fractionation factor

$\delta D_{C_{29}}$  = hydrogen isotope ratio of nonacosane

$\delta D_{C_{23}}$  = hydrogen isotope ratio of tricosane

$\varepsilon_{\text{vasc}}$  = enrichment factor between acrotelm water and nonacosane

$\varepsilon_{\text{sph}}$  = enrichment factor between Sphagnum water and tricosane

$f$  = fraction of water remaining after evaporation.

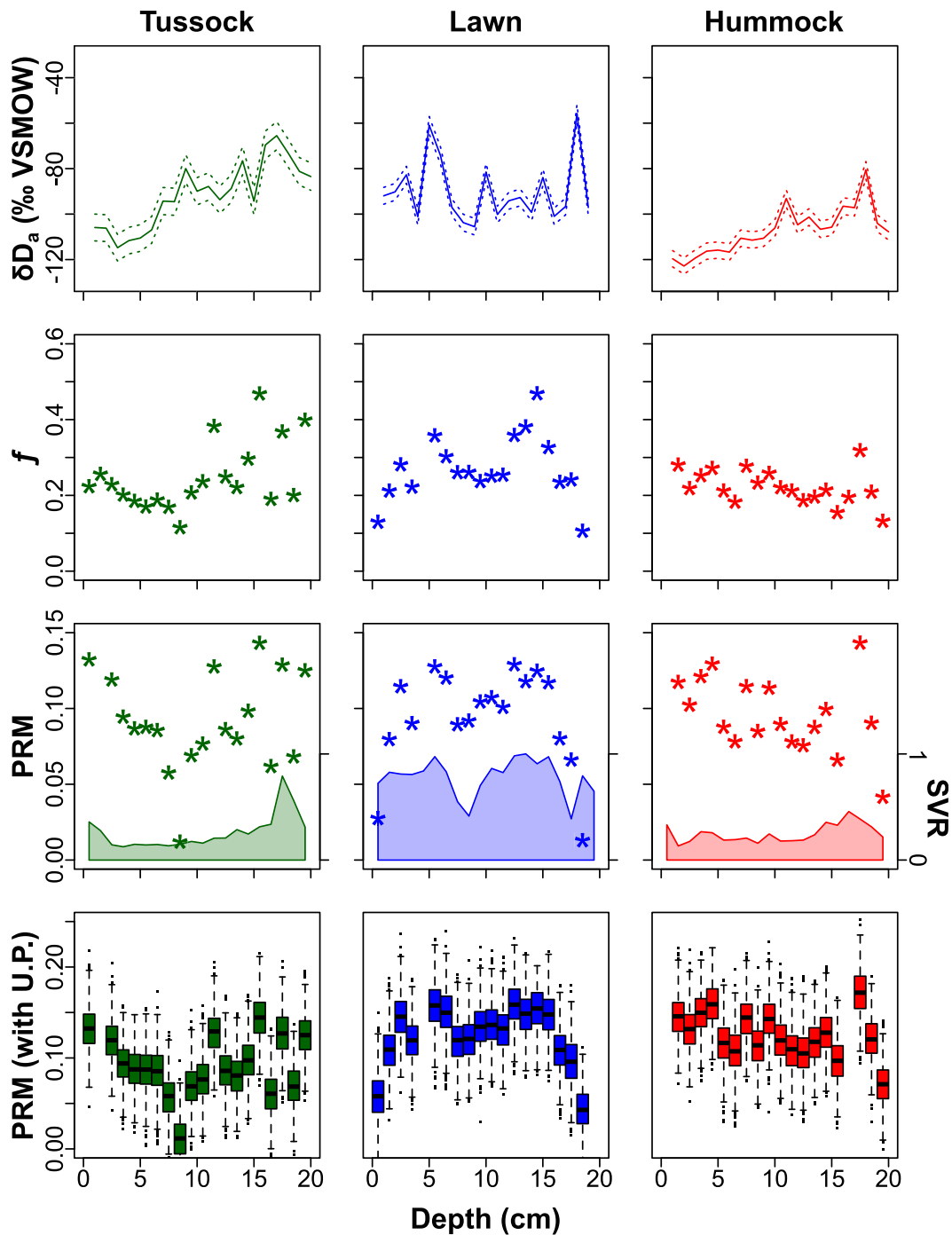
Values for kinetic and equilibrium fractionation in equation (1) ( $\varepsilon_k$  and  $\varepsilon^*$ , respectively) assume a temperature of 288 K and a relative humidity of 75%. These assumed values are reasonable for any region containing peatlands [Halsey *et al.*, 2000], and do not have a strong effect on the calculated value for  $\ln f$  [Nichols *et al.*, 2010]. In equation (2),  $\delta D_s$  is calculated using an experimentally derived relationship [Nichols *et al.*, 2010].  $\delta D_a$  is derived from the  $\delta D$  of nonacosane using an apparent fractionation for C3 dicotyledons,  $-113\text{‰}$  [Sachse *et al.*, 2006; Smith and Freeman, 2006] in the hummock and lawn locations and an apparent fractionation for C3 monocotyledons,  $-146\text{‰}$  in the tussock core [Sachse *et al.*, 2012]. By using fractionation factors that correspond with the dominant vascular vegetation, we find  $\delta D_p$  values that are consistent among the three locations (supporting information Table A1). Because the age/depth relationship is different for each core, we do not expect perfect depth-for-depth matches, but we do see a close relationship between the tussock and hummock cores (Figure 3).

The apparent fractionation factor between vascular plant leaf wax  $\delta D$  and peatland water  $\delta D$  is perhaps the largest source of uncertainty in our calculations. Much work has been done to understand the controls on this apparent fractionation, and recent publications have cautioned against direct translation of leaf wax  $\delta D$  into precipitation  $\delta D$  because of the impact of leaf water enrichment [Smith and Freeman, 2006; Hou *et al.*, 2008; Kahmen *et al.*, 2013a, 2013b]. The characteristics of peatland environments, however, minimize the effects of leaf water evaporative enrichment. Leaf water enrichment strongest in environments with low relative humidity [Hou *et al.*, 2008; Kahmen *et al.*, 2013a]. Peatlands necessarily exist in areas of very high relative humidity, about 70–80% [Gorham, 1991]. The average relative humidity for Mer Bleue is well within this range, at about 75%. The influence of leaf water enrichment is also low in riparian areas [Tipple *et al.*, 2013], which are akin to peatlands in that the rooting zone of vascular plants is often saturated. Given the uncertainty in  $\varepsilon_{\text{vasc}}$ , we have attempted to account for all influences by using the empirically derived mean values for this parameter. We also attempt to propagate the uncertainty around these empirical values through our PRM calculation using a method described below. Fortunately, our PRM calculation is flexible. Even as our understanding of  $\varepsilon_{\text{vasc}}$  evolves, our framework for calculating PRM would remain unchanged, and can easily accommodate updated methods for estimating peatland water  $\delta D$ .

Once we have calculated  $f$  for each sample, we can then use  $\ln f$  to calculate the isotope discrimination factor,  $\Delta_f$ , using an experimentally derived relationship (equation (4)) between *Sphagnum* moisture content and carbon isotope discrimination shown in Figure 4 [Williams and Flanagan, 1996].

$$-7.060 \times \ln f + 14.394 = \Delta_f \quad (4)$$

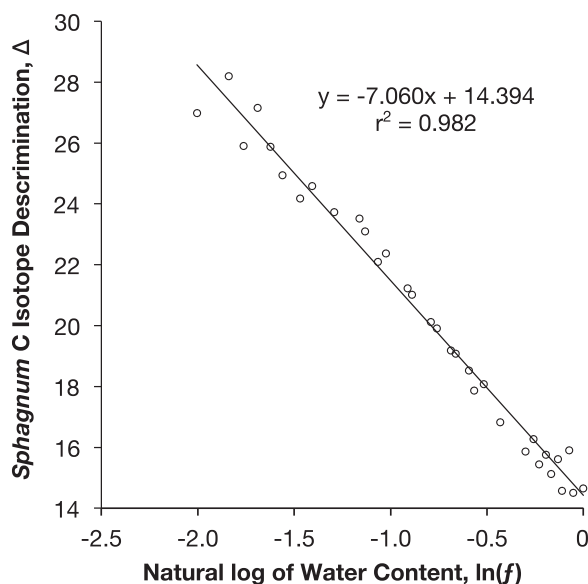
We can then use the  $\delta^{13}\text{C}$  of tricosane ( $\delta^{13}\text{C}_{C_{23}}$ ) and this enrichment factor to reconstruct this carbon isotope for the  $\text{CO}_2$  used by *Sphagnum*,  $\delta^{13}\text{C}_{\text{sph}}$  (equation (5)).



**Figure 3.** Each column contains data from one of the three monoliths, tussock, lawn, and hummock. (first row)  $\delta D$  of peatland water for each core location with 95% confidence intervals calculated from the *Sachse et al.* [2012] estimations of  $\epsilon_{\text{vasc}}$ . (second row) Calculated values for  $f$ , or the water content of *Sphagnum* based on  $\delta D$  of tricosane and nonacosane. (third row) PRM calculations along with calculations of *Sphagnum/Vascular Ratio* “SVR,” which is the proportional contribution of tricosane to the sum of tricosane and nonacosane [Nichols et al., 2006]. (fourth row) PRM with uncertainty propagation: box-and-whisker plots of 1000 instances of PRM calculation, each using different values for  $\epsilon_{\text{vasc}}$  randomly selected from a normally distributed set of values with a mean and standard deviation equal to that of the plant type as described in the text.

$$\delta^{13}\text{C}_{\text{C}_{23}} - \Delta_f = \delta^{13}\text{C}_{\text{Sph}} \quad (5)$$

The  $\text{CO}_2$  that *Sphagnum* uses, with a carbon isotope value represented by  $\delta^{13}\text{C}_{\text{Sph}}$ , is a mixture of methane respiration product and atmospheric  $\text{CO}_2$ . The percent respired-methane-derived C used by *Sphagnum* (PRM) can be calculated using a mass balance equation (equation (6)).



**Figure 4.** Carbon isotope discrimination as a function of the natural log of fractional water content. These data are redrawn from Williams and Flanagan [1996]. The regression is calculated by the least squares method.

$$\frac{\delta^{13}\text{C}_{\text{sph}} - \delta^{13}\text{C}_{\text{atm}}}{\delta^{13}\text{C}_{\text{CH}_4} - \delta^{13}\text{C}_{\text{atm}}} \times 100\% = \text{PRM} \quad (6)$$

The two end-member mass balance equation (equation (6)) is used to calculate how much carbon in *Sphagnum* comes from methane respired by symbiotic methanotrophs as a percent of the total carbon. The end-members are the measured carbon isotope ratio of methane from this peatland,  $-75\text{‰}$  [Roulet *et al.*, 2007], and the carbon isotope ratio of the local atmosphere. Rather than using a fixed value for  $\delta^{13}\text{C}$  of atmospheric  $\text{CO}_2$ , we reconstructed this value from the  $\delta^{13}\text{C}$  of nonacosane (equation (7)) using average enrichment values for bulk C3 plants ( $-20.1\text{‰}$ ) and for the

enrichment between bulk plant material and leaf wax *n*-alkanes ( $-6.4\text{‰}$ ) [Conte *et al.*, 2003; A Hobbie and Werner, 2004].

$$(\varepsilon_{\text{C}_3} + \varepsilon_{\text{alk}}) + \frac{[(\varepsilon_{\text{C}_3} + \varepsilon_{\text{alk}}) \times \delta^{13}\text{C}_{\text{C}_{29}}]}{1000} \delta^{13}\text{C}_{\text{C}_{29}} = \delta^{13}\text{C}_{\text{atm}} \quad (7)$$

By reconstructing this value, rather than using an assumed value based on the whole atmosphere, we account for the potential isotopic effects of the addition of  $\text{CO}_2$  from other sources of respiration, thus isolating the contribution of respired methane. This is necessary because the local atmosphere near the surface of peatlands can be depleted in  $^{13}\text{CO}_2$  relative to the whole atmosphere due to the addition of  $\text{CO}_2$  from respiration. The value,  $\delta^{13}\text{C}_{\text{atm}}$  represents the carbon isotope value of  $\text{CO}_2$  used by plants without methanotrophic symbionts. Using this approach, we find reconstructed values for atmospheric  $\text{CO}_2$  of  $-7.05\text{‰} \pm 0.48$ . This is consistent with direct atmospheric measurements globally. This consistent value for atmospheric  $\text{CO}_2$  also supports the conclusion that respired methane is not an important component of the atmosphere directly above the peatland surface, suggesting that most of the  $\text{CO}_2$  from respired methane is reincorporated into *Sphagnum* and not released to the atmosphere.

Because the apparent fractionation factor between water and lipids for vascular plants ( $\varepsilon_{\text{vasc}}$ ) is a large source of uncertainty, we propagated this uncertainty through our PRM calculation. For each depth interval in the three cores, we calculated the PRM 1000 times, each time choosing an  $\varepsilon_{\text{vasc}}$  at random from a normally distributed population of values with a mean and standard deviation equal to that reported in the literature for each vegetation type: for the tussock core, we use the value for C3 monocots ( $\mu = -146$ ,  $\sigma = 27$ ) and for the hummock and lawn cores we used values for C3 dicots ( $\mu = -113$ ,  $\sigma = 30$ ) [Sachse *et al.*, 2012]. The results of the PRM calculations with the propagation of uncertainty are displayed in Figure 4.

### 3.1. Percent Respired Methane at Mer Bleue

We applied our PRM calculation to sediments from the three different locations at Mer Bleue, a *Sphagnum capillifolium*-dominated lawn, the *Sphagnum magellanicum*-dominated hummock, and an *Eriophorum vaginatum* tussock with *Sphagnum capillifolium*. Uptake of respired methane by *Sphagnum* at all three locations was up to 16% (Figure 3). The range of values is reasonable, given the maximum of 20% assimilation of methane-derived carbon by *Sphagnum* samples in vitro [Raghoebarsing *et al.*, 2005].

Respired methane is a greater source of carbon for *Sphagnum* in the Lawn habitat with a higher water table than in Hummock habitat with a lower water table. This is a reasonable result, as laboratory experiments

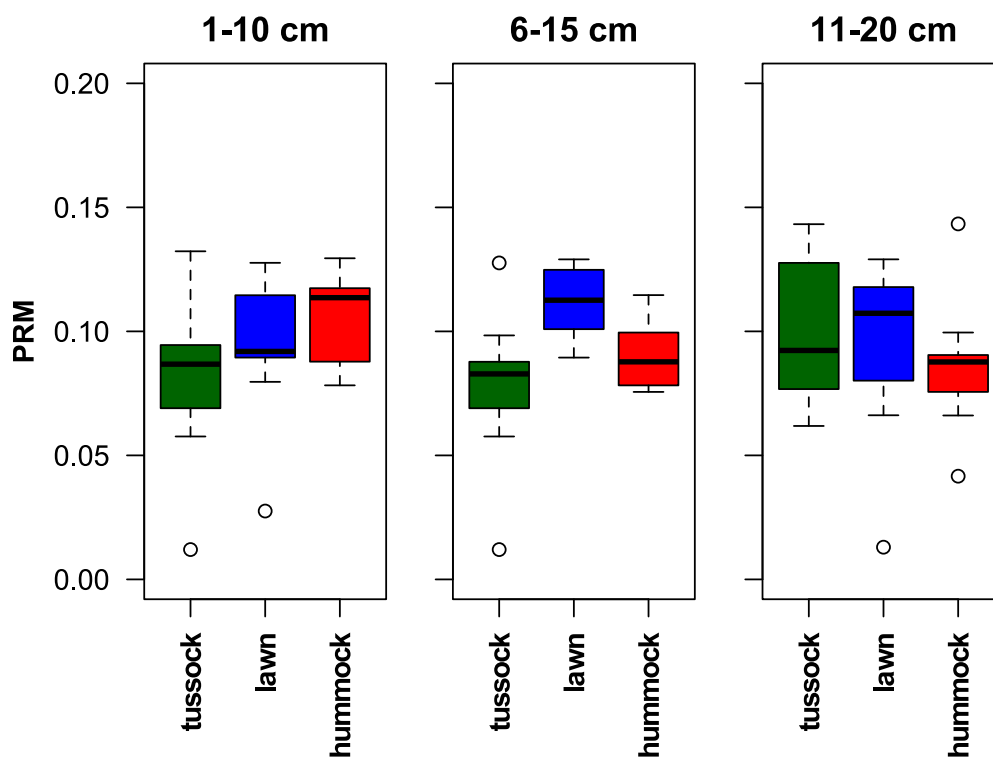


Figure 5. Box-and-whisker plots of PRM values from three sections of each of the cores.

have shown that methane consumption by symbiotic methanotrophs is greater when the *Sphagnum* is wetter [Raghoebarsing *et al.*, 2005] and that the potential for methane consumption is greater in *Sphagnum* found in peatland areas where the water table is higher [Basiliko *et al.*, 2004; Kip *et al.*, 2010]. If water table were the only factor controlling methane consumption, we would expect that the PRM would be lowest at the Hummock site, with the lowest water table. The PRM values at the Hummock site are often, but not consistently lower than at the Lawn site. Additionally, we find that the Tussock site has consistently lower PRM values than the other two sites (Figures 3 and 5).

Methanotrophs living at the Tussock site likely have less access to methane produced in the peatland, contributing to lower PRM values at this site. Sedges, including *Eriophorum vaginatum* have aerenchyma, structures which allow air from the atmosphere to oxygenate the plant's roots. These structures also allow methane to escape the peatland into the atmosphere, making it unavailable to methanotrophs in *Sphagnum*. Direct measurements of methane flux at the three sites show the presence of *Eriophorum* results in a threefold to fourfold increase in flux when water table is constant [Moore *et al.*, 2011]. Aerenchymous plants are thus a likely cause for reduced PRM values at the Tussock site. PRM values at the tussock site are not always low, however, especially in the 11–20th centimeters of the monolith (Figure 5). These samples could correspond to times when sedge stomata were, on average, closed for more time, inhibiting the flow of methane through the aerenchyma, causing the Tussock site to behave more like the Lawn site. Alternatively, there may have been fewer sedges at the site during the time represented by these samples. Indeed the relative amount of tricosane is higher in these samples than in the upper part of the monolith (Figure 3) suggesting that more *Sphagnum* was present at that time.

#### 4. Conclusions

We find that the confounding effects of water content and carbon source on carbon isotope ratios of *Sphagnum* compounds can be disentangled by our combined hydrogen and carbon isotope approach. Using this new method, we are able to quantify the proportion of carbon from methane assimilated by



*Sphagnum*, and reconstruct changes in this important carbon cycle parameter in the past. We find, as before, that water table depth and vegetation have strong influences on methane recycling by *Sphagnum*'s methanotrophic symbionts. This new method, however, allows us to quantitatively reconstruct past variability in this symbiosis. Thus, it is possible to test the relationships among hydrology, vegetation, and methanotrophy in *Sphagnum* peatlands over Holocene time scales. It is now possible to reconstruct paleohydrology, vegetation change, and methane recycling using the same samples. Such reconstructions are vital to the understanding of the methane cycle in northern peatlands. While the PRM calculation is an important step forward in our understanding of the complicated nature of *Sphagnum*  $\delta^{13}\text{C}$  measurements, further investigation is needed to connect PRM to concentrations of methane in the atmosphere.

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