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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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, δ¹³C 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 though 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 [Bridgham 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...
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 CO₂ produced by methane oxidation for photosynthesis [Raghoebarsing et al., 2005; Kip et al., 2010; Larmola et al., 2010]. The resulting O₂ 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 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 aerechyma, 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.
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$_2$ that results from the oxidation of that methane also has a distinct carbon isotope ratio. *Sphagnum* using this CO$_2$ 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 δD 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$_2$ 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 δ$^{13}$C of methane derived and atmospheric CO$_2$ 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$_2$ 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 Delta+ 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$_3^+$ 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...
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 δ13C of CO2 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].

\[
\delta D_w - \delta D_v \quad \frac{e_k - e^c}{e_k} = \ln f
\]
\[ e_{\text{vasc}} = \left( \frac{e_{\text{vasc}} \times \delta D_{\text{C29}}}{1000} \right) + \delta D_{\text{C29}} = \delta D_{a} \]  
\[ e_{\text{sph}} = \left( \frac{e_{\text{sph}} \times \delta D_{\text{C23}}}{1000} \right) + \delta D_{\text{C23}} = \delta D_{s} \]

where
\( \delta D_{a} \) = acrotelm water
\( \delta D_{s} \) = Sphagnum water
\( e_{k} \) = kinetic fractionation factor
\( e^{*} \) = equilibrium fractionation factor
\( \delta D_{\text{C29}} \) = hydrogen isotope ratio of nonacosane
\( \delta D_{\text{C23}} \) = hydrogen isotope ratio of tricosane
\( e_{\text{vasc}} \) = enrichment factor between acrotelm water and nonacosane
\( e_{\text{sph}} \) = enrichment factor between Sphagnum water and tricosane
\( f \) = fraction of water remaining after evaporation.

Values for kinetic and equilibrium fractionation in equation (1) (\( e_{k} \) and \( e^{*} \), 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), \( \delta D_{a} \) is calculated using an experimentally derived relationship [Nichols et al., 2010]. \( \delta D_{s} \) is derived from the \( \delta D \) of nonacosane using an apparent fractionation for C3 dicotyledons, \(-113^{\%}_{\text{on}}\) [Sachse et al., 2006; Smith and Freeman, 2006] in the hummock and lawn locations and an apparent fractionation for C3 monocotyledons, \(-146^{\%}_{\text{on}}\) in the tussock core [Sachse et al., 2012]. By using fractionation factors that correspond with the dominant vascular vegetation, we find \( \delta D_{s} \) 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 \( e_{\text{vasc}} \), 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 \( e_{\text{vasc}} \) 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, \( \Delta_{r} \), using an experimentally derived relationship (equation (4)) between Sphagnum moisture content and carbon isotope discrimination shown in Figure 4 [Williams and Flanagan, 1996].

\[ -7.060 \times \ln f + 14.394 = \Delta_{r} \]  

We can then use the \( ^{13}C \) of tricosane \( (^{13}C_{\text{C23}}) \) and this enrichment factor to reconstruct this carbon isotope for the CO\(_{2}\) used by Sphagnum, \( ^{13}C_{\text{sph}} \) (equation (5)).
The CO₂ that Sphagnum uses, with a carbon isotope value represented by \( \delta^{13}C_{\text{sph}} \), is a mixture of methane respiration product and atmospheric CO₂. The percent respired-methane-derived C used by Sphagnum (PRM) can be calculated using a mass balance equation (equation (6)).

\[
\delta^{13}C_{\text{in}} - \Delta_f = \delta^{13}C_{\text{sph}}
\]  

The CO₂ that Sphagnum uses, with a carbon isotope value represented by \( \delta^{13}C_{\text{sph}} \), is a mixture of methane respiration product and atmospheric CO₂. The percent respired-methane-derived C used by Sphagnum (PRM) can be calculated using a mass balance equation (equation (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, $^{13}C_{\text{atm}}$, and the carbon isotope ratio of the local atmosphere. Rather than using a fixed value for $^{13}C_{\text{atmospheric CO}_2}$, we reconstructed this value from the $^{13}C$ of nonacosane (equation (7)) using average enrichment values for bulk C3 plants ($\delta^{13}C_{\text{alk}} = -20.1\%_O$) and for the enrichment between bulk plant material and leaf wax n-alkanes ($\delta^{13}C_{\text{alk}} = -6.4\%_O$) [Conte et al., 2003; A Hobbie and Werner, 2004].

$$\frac{\delta^{13}C_{\text{ph}} - \delta^{13}C_{\text{atm}}}{\delta^{13}C_{\text{CH}_4} - \delta^{13}C_{\text{atm}}} \times 100\% = \text{PRM}$$

(6)

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 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 $^{13}$CO$_2$ relative to the whole atmosphere due to the addition of CO$_2$ from respiration. The value, $\delta^{13}C_{\text{atm}}$ represents the carbon isotope value of CO$_2$ used by plants without methanotrophic symbionts. Using this approach, we find reconstructed values for atmospheric CO$_2$ of $27.05\%_O \pm 0.48$. This is consistent with direct atmospheric measurements globally. This consistent value for atmospheric 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 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 ($e_{\text{vasc}}$) 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 $e_{\text{vasc}}$ 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...
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 variabil-
ity in this symbiosis. Thus, it is possible to test the relationships among hydrology, vegetation, and metha-
notrophy 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 δ13C measurements,
further investigation is needed to connect PRM to concentrations of methane in the atmosphere.

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References
Booth, R. K. (2002), Testate amoebae as paleoindicators of surface-moisture changes on Michigan peatlands: Modern ecology and hydro-
Bush, R. T., and F. A. McInerney (2013), Leaf wax n-alkane distributions in and across modern plants: Implications for paleoecology and che-
CH4 gradient between Greenland and Antarctica during the Last Glacial and the transition to the Holocene, J. Geophys. Res., 102(D13), 15,987–15,997.
Chen, Y., M. Dumont, N. McNamara, and P. Chamberlain (2008), Diversity of the active methanotrophic community in acidic peatlands as
Conte, M., J. Weber, P. Carlson, and L. Flanagan (2003), Molecular and carbon isotopic composition of leaf wax in vegetation and aerosols
Dallenbach, A., T. Blunier, J. Fluckiger, B. Stauffer, J. Chappellaz, and D. Raynaud (2000), Changes in the atmospheric CH4 gradient between
Greenland and Antarctica during the Last Glacial and the transition to the Holocene, J. Geophys. Res. Lett., 27(7), 1005–1008.
Frenzel, P., and E. Karofeld (2000), CH4 emission from a hollow-ridge complex in a raised bog: The role of CH4 production and oxidation,
Halsey, L., D. Vitt, and L. Gignac (2000), Sphagnum-dominated peatlands in North America since the last glacial maximum: Their occurrence
and extent, Bryologist, 103(2), 334–352.
Hobbie, E. A., and R. A. Wener (2004), Intramolecular, compound-specific, and bulk carbon isotope patterns in C3 and C4 plants: A review and
Hornbrook, E., H. L. Bowes, A. Culbert, and A. V. Gallego-Sala (2009), Methanotrophy potential versus methane supply by pore water dif-
sion in peatlands, Biogeosciences, 6, 1491–1504.
Hou, J., W. D’Andrea, and Y. Huang (2008), Can sedimentary leaf waxes record D/H ratios of continental precipitation? Field, model, and
Kahmen, A., B. Hoffmann, E. Schefuß, L. A. Cernusak, J. B. West, and D. Sachse (2013a), Leaf water deuterium enrichment shapes
leaf wax n-alkane δ13C values of angiosperm plants II: Observational evidence and global implications, Geochim. Cosmochim. Acta, 111, 50–60,
Kahmen, A., E. Schefuß, and D. Sachse (2013b), Leaf water deuterium enrichment shapes leaf wax n-alkane δ13C values of angiosperm
Kim, J., and S. Verma (1996), Surface exchange of water vapour between an open Sphagnum fen and the atmosphere, Boundary Layer Meteoro-
Camp (2010), Global prevalence of methane oxidation by symbiotic bacteria in peat-moss ecosystems, Nat. Geosci., 3(9), 617–621, doi:
10.1038/ngeo939.
Korhola, A., M. Ruppel, H. Seppä, M. Välimäki, T. Virtanen, and J. Weckström (2010), The importance of northern peatland expansion to the
Laanbreck, H. J. (2010), Methane emission from natural wetlands: Interplay between emergent macrophytes and soil microbial processes.
Lesel, J., M. Garneau, and J. Hélie (2009), Modern Sphagnum δ13C signatures follow a surface moisture gradient in two boreal peat bogs,
Markel, E. R., R. K. Booth, and Y. Qin (2010), Testate amoebae and δ13C of Sphagnum as surface-moisture proxies in Alaskan peatlands, Holo-
Möller, L. T., S. Sowers, M. Bock, R. Spahn, and M. Behrens (2013), Independent variations of CH4 emissions and isotopic composition over
the past 160,000 years, Nat. Geosci., 6, 885–890, doi:10.1038/ngeo1922.


