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Short Communication – FINAL REVISION

Woody stem methane emission in mature wetland alder trees

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Abstract

Methane (CH$_4$) is an important greenhouse gas that is predominantly emitted to the atmosphere from anoxic wetland ecosystems. Understanding the sources and emissions of CH$_4$ is crucially important for climate change predictions; however, there are significant discrepancies between CH$_4$ source estimates derived via so-called bottom-up and top-down methods. Here we report CH$_4$ emission from the stems of mature wetland alder (Alnus glutinosa) trees in the UK, a common tree of northern hemisphere floodplains and wetlands. The alder stems most likely behave as conduits for soil-produced CH$_4$ either in the gaseous or aqueous phase, and may, therefore, help to reconcile methodological differences in the way the wetland CH$_4$ source is estimated.

Alder tree stems emitted average peak CH$_4$ fluxes of 101 µg CH$_4$ m$^{-2}$ hr$^{-1}$ (on a stem area basis) in early October, a rate that is similar to that obtained from mature Japanese ash (Fraxinus mandshurica var. japonica) in Japan and amounting to approximately 20% of the measured CH$_4$ flux from the soil surface. The finding suggests that trees, which occupy 60% of Earth’s wetlands and are normally excluded from the measurement programmes that form the basis for bottom-up estimates of the global wetland source, could be important contributors to overall terrestrial ecosystem CH$_4$ flux.
Introduction

Wetlands form the largest source of methane (CH$_4$) to the atmosphere, a powerful greenhouse gas that is thought to have contributed approximately 50% of the enhanced greenhouse effect of CO$_2$ since 1850 (Hansen et al., 2000). Great importance is therefore placed on characterizing the various CH$_4$ sources and emission pathways to enable changes observed in atmospheric growth rate to be better understood. Methane has received considerable recent attention as satellite and airborne measurements have yielded an unexpected spatial distribution of sources with strong emission plumes identified over tropical forests, many of which are seasonally flooded (Frankenberg et al., 2005; Miller et al., 2007). In many such regions, there continues to be a discrepancy between bottom-up emissions-based estimates and top-down inverse or satellite-based estimates of the CH$_4$ source (Frankenberg et al., 2008).

The recent reporting of novel aerobic CH$_4$ production pathways in plants (Keppler et al., 2006) has been invoked as a potential explanation for discrepancies between low, bottom-up and high, top-down satellite-based or inverse method derived estimates of CH$_4$ sources. However, the large size estimates initially made for this hypothesized source (up to ~240 Tg CH$_4$ yr$^{-1}$ (Keppler et al., 2006)) have since been revised down to between zero and 85 Tg CH$_4$ (e.g. Howelling et al., 2006; Dueck et al., 2007). Here we provide evidence for a more straightforward and almost completely overlooked pathway for CH$_4$ emissions from anaerobic soils and sediments that may account for at least part of the discrepancy in the way CH$_4$ sources and balances are estimated.

Emission of CH$_4$ produced in anaerobic soils to the atmosphere is the largest individual source of CH$_4$. Fluxes are thought to be controlled by three transport mechanisms: diffusion, ebullition and vascular transport in herbaceous plants, all of which are measurable using established small-scale enclosure methods. In peatlands, aerenchyma in sedges and
certain other vascular plants allows CH$_4$ to bypass an oxic 'acrotelm' layer at the top of the peat column (Joabsson et al. 1999). Without this escape route, methanotrophic bacteria in the acrotelm would consume a large proportion of produced CH$_4$. Aerenchyma tissue provides a diffusion pathway for oxygen, enabling sedges and other herbaceous wetland plants to maintain active roots in anoxic environments (Armstrong and Boatman, 1967). Similarly, flood-tolerant trees growing in soil with a high water table or exposed to periodically flooded conditions develop important adaptations that collectively facilitate oxygen supply to roots, thus preventing hypoxia (Kozlowski 1997). Such features are classically evident in trees such as mangrove and swamp cypress where morphological adaptations, principally aerial roots and pneumatophores, facilitate gaseous exchange, and from which CH$_4$ emission has been measured (Vann and Megonigal 2003; Purvaja et al., 2004). However, many other tree species also grow under flooded conditions without overtly exhibiting such morphological adaptations. The trees prevent hypoxia via the formation of aerenchyma in root tissue and hypertrophied lenticels on tree stems and submerged roots (Kozlowski 1997).

A relatively unexplored pathway of CH$_4$ flux from such wetland trees is the transfer of anaerobically-produced CH$_4$ from soils into roots via the aqueous phase, and emission to the atmosphere via transpiration. This mechanism is similar to that described for N$_2$O transport in Fagus sylvatica, (e.g. Pihlatie et al. 2005) and, like N$_2$O, there are no physical or chemical barriers to the entry of apolar dissolved CH$_4$ into roots during uptake of soil water. The CH$_4$-bearing water can be transported through xylem tissue, ultimately releasing CH$_4$ to the troposphere via leaf stomata or lenticels. This emission pathway may be an important mechanism for mediating CH$_4$ flux from wetland- or fine-textured soils where moisture levels allow for the existence of anaerobic microsites (Teh et al., 2005).

The only previous report of CH$_4$ flux from mature, non-pneumatophore-forming trees was made for Japanese ash (Fraxinus mandshurica var. japonica (Terazawa et al., 2007)).
Other species have not been investigated in mature trees, despite the morphological features thought to be responsible for CH$_4$ emission being reported for a wide range of tree species (e.g. Kozlowski 1997).

Here we report findings from a study to examine the potential for a new family of mature freshwater wetland trees to serve as a conduit for trace gas transport to the atmosphere. Common or Black Alder (*Alnus glutinosa*) are the most common tree species in riparian forests and are found throughout Europe, Russia and Siberia and are also commonly found in the Northeast USA and Eastern Canada. Taken together with the work of Terazawa *et al.* (2007), our study is designed to examine the potential for a wide variety of wetland trees to collectively serve as a significant source of CH$_4$ to the atmosphere.

**Methods**

We examined CH$_4$ emission from *Alnus glutinosa* trees at Flitwick Moor nature reserve in Bedfordshire, United Kingdom (52°00' N, 00°28' W). Three mature trees having diameters of 10 to 30 cm at a height of 30 cm above the forest floor were selected for the study. The site consists of a peat soil which is spring fed which allows the water-table to remain consistently at or just above the soil surface. Three site visits were made from May to October 2006 to monitor changes in headspace CH$_4$ concentration with time in temporary gas-exchange chambers that enclosed the entire stem section 30 cm above the forest floor for 3 hours. The chambers were constructed from four clear acrylic walls, each having dimensions of 500 x 350 x 6 mm (Figure 1). The headspace was defined by enclosing the volume with transparent sheets of gas-impermeable FEP film (Adtech Ltd.) to form the top and bottom of the enclosure. Strips of closed cell foam (3-cm wide) were attached to the stem 35 cm apart, providing an effective seal with the tree on which the FEP film could be attached. Measurements were initiated at approximately midday, and headspace samples (3 x 20 ml) were drawn via a septum into 3 gas-tight syringes fitted with 3-way valves at t = 0,
60, 120, 180 minutes. The samples were transported to the lab within 48 hours for analysis using a Cambridge AI gas chromatograph (GC) equipped with a flame ionisation detector (FID) with a measured [CH$_4$] standard error of 23 ppbv. The minimum measurable flux using our approach was 2.4 µg CH$_4$ m$^{-2}$ hr$^{-1}$. Soil CH$_4$ fluxes were measured during the October sampling from 3 chambers positioned on the ground surface using established methods (Gauci et al., 2002). Fluxes were estimated using linear regression analysis of the change in headspace methane concentration with time. The phonological status of the sampled trees was also recorded at each site visit. During the May site visit, alder tree leaves had yet to emerge on sampled trees. In June leaves had fully emerged and in October the trees remained in full leaf.

**Results and Discussion**

Significant tree stem CH$_4$ emission was measured during each sampling visit (linear regression analysis, P < 0.05). Fluxes (expressed per unit area of stem) ranged from a mean of 4.1 µg CH$_4$ m$^{-2}$ hr$^{-1}$ in May to 101 µg CH$_4$ m$^{-2}$ hr$^{-1}$ in early October (Table 1), the peak month measured. Stem fluxes measured in October were about 20% of soil fluxes measured at the same time (536 µg CH$_4$ m$^{-2}$ hr$^{-1}$). They were also of the same order of magnitude as CH$_4$ fluxes measured from mature *Fraxinus mandshurica* sp. in Japan (Terazawa et al., 2007). In contrast to the Japanese study, CH$_4$ fluxes from Flitwick Moor showed a pronounced seasonal pattern, being an order of magnitude smaller in spring than summer and autumn.

Collectively, our data and those of Terazawa et al., (2007) suggest that many wetland trees that lack outwardly obvious morphological features commonly associated with flood adaptation and gas transport may emit CH$_4$ that has been produced in anaerobic soils. The data further suggest that estimates of CH$_4$ flux from forested wetlands, whether seasonally or
permanently flooded, are likely to underestimate the emission of anaerobically-produced CH$_4$ if trees are excluded from measurement. For example, the development of hypertrophied lenticels in response to flooding has been reported for 15 angiosperm and 22 gymnosperm species (Kozlowski 1997 and references therein) and root aeration via either pressurised gas transport or stem photosynthesis has been measured in genera of Alnus and Salix as well as Betula pubescens, Populus tremula and Taxodium distichum (Grosse et al. 1996; Armstrong and Armstrong 2005). These morphological adaptive features to flooding, together with our findings of CH$_4$ emission from the stems of mature Alnus glutinosa and fluxes reported by Terazawa et al. (2007), suggest that gaseous and/or aqueous phase transport of CH$_4$ (and possibly other trace gases) may be common among trees adapted to wet soils in both temperate and tropical forested wetland ecosystems.

The development of aerenchyma has also been reported in the roots of tree species that normally experience prolonged saturated conditions in central Amazonian várzeas (De Simone et al. 2002). This area is particularly interesting because it has been the site of numerous soil chamber-based CH$_4$ flux measurements (e.g., Bartlett et al., 1988, 1990; Crill et al., 1988; Devol et al., 1988; Wassmann et al., 1992; Engle & Melack, 2000), all of which excluded tree stems. Scaling up these chamber-based estimates of methane emission consistently results in lower regional CH$_4$ estimates than top-down flight data estimates (Miller et al., 2007).

Evidence therefore suggests that this ‘woody plant pathway’ first proposed by Rusch and Rennenberg (1998) may be important in forested wetland ecosystems and could have implications for global CH$_4$ emission inventories. Given that 60% of Earth's wetlands are forested (Matthews and Fung 1987) and that the majority of CH$_4$ flux studies have used chamber sampling methods that exclude trees, this mechanism may represent an important uncharacterised component of terrestrial CH$_4$ flux. Omission of this pathway from process
models may result in an underestimation of total CH₄ emissions from global wetlands.

The ‘fourth pathway’ of stem methane emission (in addition to pore water diffusion, herbaceous aerenchymatous transport, and ebullition) may help to reconcile differences between smaller, emission-based (‘bottom up’) estimates of the global CH₄ source (Matthews and Fung 1987; Aselman and Crutzen 1989; Cao et al 1996) and larger atmospheric chemistry-based inverse (‘top down’) estimates (e.g. Houweling et al 1999).

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References


Figure and Table Captions:

Figure 1 Experimental methods for measuring methane fluxes from stems of *Alnus glutinosa*

Table 1 Tree stem (T) and forest floor (S) methane emission rates for Flitwick Moor in 2006.
R² values are derived from linear regression analysis. SD = standard deviation
**Table 1** Tree stem (T) and forest floor (S) methane emission rates for Flitwick Moor in 2006. $R^2$ values are derived from linear regression analysis. SD = standard deviation.

<table>
<thead>
<tr>
<th>Date</th>
<th>Chamber (T = Tree, S = Soil)</th>
<th>Tree Diameter /m</th>
<th>CH$_4$ flux ($\mu$gCH$_4$m$^{-2}$hr$^{-1}$)</th>
<th>$R^2$ of regression (all $P&lt;0.05$, n=6)</th>
<th>Mean CH$_4$ flux ($\mu$gCH$_4$m$^{-2}$hr$^{-1}$) (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>3$^{rd}$ May</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T1</td>
<td>0.3</td>
<td>4.37</td>
<td>0.99</td>
<td></td>
<td>4.1 (0.8)</td>
</tr>
<tr>
<td>T2</td>
<td>0.18</td>
<td>4.78</td>
<td>0.97</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T3</td>
<td>0.16</td>
<td>3.22</td>
<td>0.83</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>8$^{th}$ June</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T1</td>
<td>0.3</td>
<td>35.7</td>
<td>0.70</td>
<td></td>
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</tr>
<tr>
<td>T2</td>
<td>0.18</td>
<td>26.4</td>
<td>0.97</td>
<td></td>
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</tr>
<tr>
<td>T3</td>
<td>0.16</td>
<td>132</td>
<td>0.90</td>
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<td>65 (59)</td>
</tr>
<tr>
<td><strong>12$^{th}$ October</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>T1</td>
<td>0.3</td>
<td>92.6</td>
<td>0.71</td>
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<tr>
<td>T2</td>
<td>0.18</td>
<td>126.5</td>
<td>0.85</td>
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<tr>
<td>T3</td>
<td>0.16</td>
<td>84.2</td>
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<td>101 (22)</td>
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<tr>
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<td>328</td>
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</tr>
<tr>
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<td>441</td>
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<tr>
<td>S3</td>
<td></td>
<td>838</td>
<td>0.86</td>
<td></td>
<td>536 (268)</td>
</tr>
</tbody>
</table>
**Figure 1** Experimental methods for measuring methane fluxes from stems of *Alnus glutinosa.*