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Emissions of Anaerobically Produced Methane by Trees

Andrew L. Rice
Portland State University

Christopher Lee Butenhoff
Portland State University

Martha J. Shearer
Portland State University

Doaa Teama
Portland State University

Todd N. Rosenstiel
Portland State University

See next page for additional authors

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Emissions of anaerobically produced methane by trees

Andrew L. Rice,[1] Christopher L. Butenhoff,[1] Martha J. Shearer,[1] Doaa Teama,[1] Todd N. Rosenstiel,[2] and M. Aslam K. Khalil[1]

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[1] Recent studies indicate that plants may be a previously overlooked but significant source of atmospheric CH_4, though there is considerable disagreement on the mechanism of production. Our work sought to verify that woody deciduous trees grown under inundated conditions had the capacity for transporting CH_4 from an anaerobic subsurface to the atmosphere and to consider if such a source could be important globally. Here, we report results from a greenhouse mesocosm study that indicate significant emissions of anaerobically produced CH_4 transmitted to the atmosphere through broadleaf riparian tree species grown under flooded conditions. Using a leaf area normalized mean emission rate (0.7 ± 0.3 μg cm^{-2} hr^{-1}), results were scaled globally for flooded forest regions and estimated to be 60 ± 20 Tg year^{-1}, ~10% of the global CH_4 source. The carbon isotopic composition of CH_4 emitted was found to be significantly enriched compared with expectations ($\delta^{13}C \sim -54‰$) and provided an important isotopic constraint on the global source which coincides with the mean of the globally scaled greenhouse-based estimate. **Citation:** Rice, A. L., C. L. Butenhoff, M. J. Shearer, D. Teama, T. N. Rosenstiel, and M. A. K. Khalil (2010), Emissions of anaerobically produced methane by trees, *Geophys. Res. Lett.*, *37*, L03807, doi:10.1029/2009GL041565.

1. Introduction

[2] Methane (CH_4) is an important radiative and chemically reactive trace gas that has more than doubled in concentration in the Earth's atmosphere over the past 200 years as a result of mankind's activities, primarily rice cultivation, ruminant animal husbandry, biomass burning, and fossil fuel usage [*Rasmussen and Khalil*, 1984]. Despite more than two decades of research, there are considerable uncertainties in the magnitudes and trends of natural and anthropogenic sources of methane to the atmosphere. Renewed interest in atmospheric CH_4 has recently resulted from observations of larger than expected emissions in tropical forests and studies that upset the conventional wisdom by proposing that plants could produce CH_4 in oxic environments [*do Carmo et al.*, 2006; *Frankenberg et al.*, 2008; *Keppler et al.*, 2006; *Miller et al.*, 2007; *Nisbet et al.*, 2009; *Vigano et al.*, 2008; *Wang et al.*, 2008]. Both the mechanism and the magnitude of source estimations have been disputed in the literature [*Butenhoff and Khalil*, 2007; *Dueck et al.*, 2007; *Kirschbaum and Walcroft*, 2008; *Nisbet et al.*, 2009].

[3] Though there has been significant research on emissions of CH_4 from natural wetlands, early work concluded that the majority of emissions in natural wetland systems are mediated by aquatic macrophytes and through ebullition [*Cicerone and Oremland*, 1988]. Several more recent studies have indicated that woody tree systems could present a mechanism for transporting CH_4 to the atmosphere from an anaerobic root zone under inundated conditions or, potentially, bypassing an aerobic oxidation layer that lies between deep roots and the atmosphere [*Garnet et al.*, 2005; *Megonigal and Guenther*, 2008; *Rusch and Rennenberg*, 1998; *Terazawa et al.*, 2007]. These tree emissions could particularly enhance CH_4 flux in tropical regions that experience regular seasonal inundation.

[4] In this paper, we present a study of emissions of anaerobically produced CH_4 from three deciduous riparian tree species and a global upscaling of results to determine the potential of tree emissions to impact the global CH_4 budget.

2. Experimental Methods

[5] Three woody riparian tree species were grown in small mesocosms and studied in a research greenhouse: ash (*Fraxinus latifolia*), cottonwood (*Populus trichocarpa*), and willow (*Salix fluviatillis*). These experiments were conducted adjacent to ongoing mesocosm experiments with a rice cultivar reference (*Oryza sativa L.* '*M-103*') and unplanted control plots. Plants were grown in triplicate in a sandy loam (71.8% sand, 25.6% silt, 2.6% clay and 3.23% organic matter, 1.6% C, 0.12% N, 0.01% S, 126 ppm P, 101 ppm K) contained in fiberglass tubs (61 × 48 × 36 cm). Soil organic content was enhanced through the addition of rice straw equivalent to 3 tons per hectare to stimulate below ground anaerobic methane production. All plants and controls were grown under fully inundated conditions except during one mid-season drainage.

[6] Static flux samples were drawn from translucent chambers enclosing each plant and its air-water interface approximately two times weekly between July and October primarily during morning hours (9–11 AM local time). Chambers were reinforced translucent polyethylene sheeting on a frame of PVC pipe (66 × 51 × 90 cm), with a gas sampling port and a 12 Volt battery powered fan that stirred the air inside the chamber during sampling. Tedlar bag branch enclosures were also used to confirm CH_4 emissions through the tree biomass. Leaf area and above ground biomass were determined destructively at the end of the experiment.

[7] Over the course of the study, approximately 60 fluxes were measured from each species. Samples from inside the chambers were removed at 10 minute intervals for 30 minutes and CH_4 concentrations were measured on a Agilent model

[1]Department of Physics, Portland State University, Portland, Oregon, USA.
[2]Department of Biology, Portland State University, Portland, Oregon, USA.

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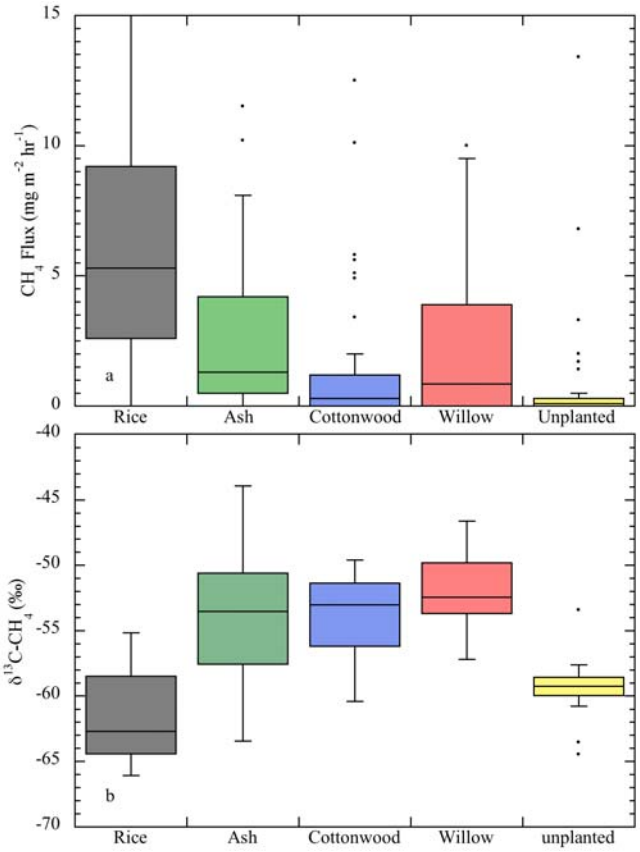

Figure 1. Box and whisker plots showing the distribution of (a) methane fluxes and (b) the carbon isotopic composition of emitted CH_4 measured for rice (black), ash (green), cottonwood (blue), willow (red), and control plots (yellow).

6890 gas chromatograph with a flame ionization detector (GC-FID) [*Khalil et al.*, 1998]. Net CH_4 flux is determined by linear regression of the change in concentration with time ($\Delta CH_4/\Delta t$) and expressed m^{-2} of water-atmosphere interface [*Khalil et al.*, 1998]. Analyses were filtered for strong ebullition events and operator error, identified by their non-linearity ($r^2 < 0.9$, ~10% of data). Belowground porewater samples at 5, 10, 15, and 20 cm depths were collected bi-weekly and CH_4 concentrations were measured by extracting samples in ultra-high purity N_2, and analyzing them *via* GC-FID.

[8] During a sampling intensive period, flux (t = 30 min) and porewater samples were drawn once per week and measured for the carbon isotopic composition ($\delta^{13}C$) of CH_4. The $\delta^{13}C$ of CH_4 was determined by continuous-flow gas chromatography-isotope ratio mass spectrometry on a Thermo Scientific Delta V Advantage IRMS using a method previously described [*Rice et al.*, 2001]. Values of $\delta^{13}C$ of CH_4 were measured relative to a calibrated CO_2 reference gas and are reported relative to the VPDB scale using the delta (δ) notation such that $\delta^{13}C = [(^{13}C/^{12}C_{sample}/^{13}C/C_{VPDB}) - 1] \times 1000$ as established by the International Atomic Energy Agency (IAEA) in Vienna, Austria [*Coplen*, 1995]. All samples were corrected for the ambient atmosphere in the greenhouse (~2 ppm CH_4), collected at initial chamber placement (t = 0 min).

[9] For purposes of global upscaling of results, inundated forests were identified using the Global Land Cover 2000 product with a spatial resolution of ~1 km [*Bartholomé et al.*, 2002]. Land cover classification included regularly and permanently flooded forests. We assumed that tropical riparian forests were flooded annually for five months which is consistent with the duration of the wet season and measurements of tropical inundation using satellite techniques [*Eva et al.*, 2002]. We assumed that mangroves and coastal forests were flooded permanently as inundation here is primarily determined by sea level [*Eva et al.*, 2002]. Tundra shrubland was considered waterlogged over the northern hemisphere summer. The canopy leaf area was derived from the Collection 5 MODIS Leaf Area Index (LAI) product at 1 km resolution [*Yang et al.*, 2006]. The monthly averages from 2000 to 2001 were used. Emissions were calculated for each grid cell *i* and month *m* by:

$$E_{i,m} = F \times LA_{i,m} \times D_{i,m} \times I_i$$

where F is the mean methane flux, LA is the leaf area, D is the number of daylight hours, and I is either 0 or 1, depending on whether the pixel is inundated during the current month. Monthly emissions were summed to annual.

3. Results and Discussion

[10] All three riparian tree species showed average flux of CH_4 greater than control, with mean emission rates of 2.6, 1.5, and 3.2 mg m^{-2} hr^{-1} for ash, cottonwood, willow and 0.9 mg m^{-2} hr^{-1} for control plots (Figure 1a). All tree plots produced lower fluxes than rice which averaged 6.6 mg m^{-2} hr^{-1}. The effect of daily temperature variations was determined to have only a small impact on CH_4 flux (temperature range 19–36°C, $r^2 = 0.14$) and no clear seasonal behavior in CH_4 flux was observed in tree fluxes [*Khalil et al.*, 1998].

[11] The flux distributions were fit using gamma distributions and the method of moments was applied to assess the variability of each species [*Rice*, 2007]. Emissions from ash, cottonwood, and willow were higher than control plots at high levels of significance (p-value < 0.01, two-sided t-test). For purposes of calculating CH_4 flux through the trees, the control plot distribution was subtracted from the aggregate tree distribution. Resulting data were then normalized to tree leaf area and the average tree CH_4 emission rate was calculated to be 0.7 ± 0.3 μg cm^{-2} hr^{-1}. This estimate is higher, but within collective error, than recent estimates of ~0.5 μg cm^{-2} hr^{-1} from Bald Cypress (*Taxodium distichum*) [*Garnet et al.*, 2005].

[12] Tedlar bag branch enclosures revealed significant emission in all species, but concentrations in the bags were non-linear on short time scales and resulting quantitative flux estimates using this approach were problematic. The origin of this response is unknown, but its rapidity is suggestive of stomatal control of CH_4 conductance [*Farquhar and Sharkey*, 1982].

[13] The $\delta^{13}C$ of emitted CH_4 from chamber enclosure and bag samples are shown in Figure 1b. Rice and control plots had $\delta^{13}C$ values of −62 ± 3‰ and −59 ± 2‰ respectively for emitted CH_4 which is characteristic of rice agriculture and anaerobic wetland environments [*Tyler et al.*, 1997]. All three tree species emitted CH_4 enriched in ^{13}C relative to rice and control plots with $\delta^{13}C$ values of −54 ±

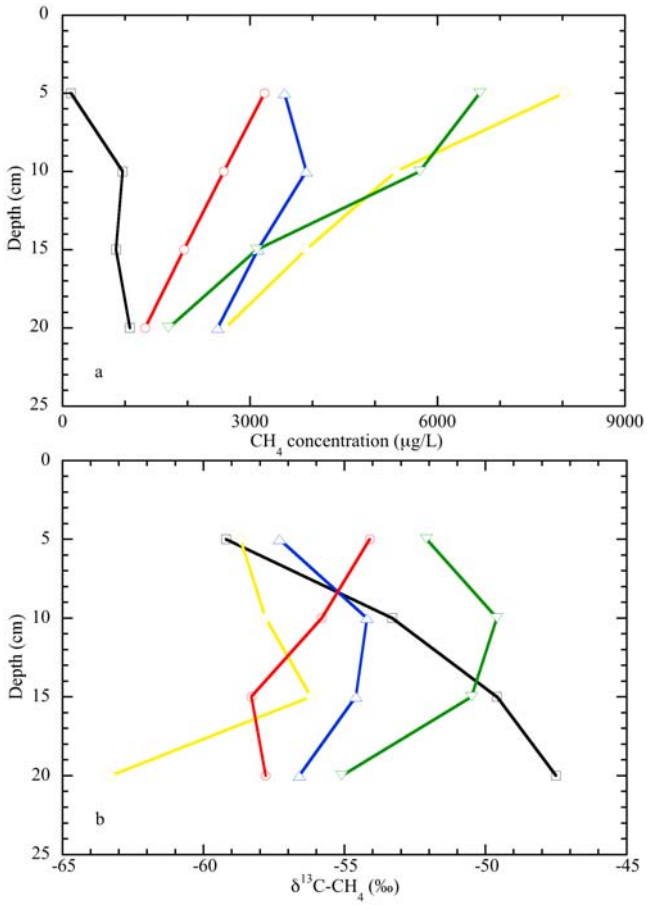

Figure 2. (a) Belowground concentrations and (b) carbon isotopic composition of CH_4 measured for rice (black squares), ash (green inverted triangles), cottonwood (blue triangles), willow (red circles), and control plots (yellow diamonds).

5‰ from ash, −54 ± 3‰ from cottonwood, and −52 ± 3‰ from willow. Though differences between tree species were not found, the difference between $\delta^{13}C$ from aggregate tree data (−54 ± 4‰) and rice plots (and controls) is significant at high levels of confidence (p-value < 0.01).

[14] The ~8‰ $\delta^{13}C$ difference between rice and tree emitted CH_4 can result from differences in CH_4 production, gas transport, or oxidation. Though recent photosynthates can be an important source of carbon for methanogenesis, all plant species used in this work were C3 in photosynthetic pathway and likely have similar isotopic signatures in their organic matter ($\delta^{13}C \sim -25‰$) [*King and Reeburgh*, 2002]. Active rhizodeposition of organic acids fixed *via* the enzyme PEP-carboxylase have been observed in some systems, including anaerobic root zones [*Johnson et al.*, 1996; *Jones*, 1998]. The enriched $\delta^{13}C$ signature observed could indicate this form of root exudates driving methanogenesis in the rhizosphere. Differences in carbon isotope fractionation factors with different methanogenic community structure could also potentially explain the observed 8‰ difference between rice and tree emitted CH_4 [*Chidthaisong et al.*, 2002].

[15] Alternatively, isotopic fractionation occurs in plants due to diffusive and effusive transport processes which are mass dependent, the magnitude of which depends largely on pore size [*Chanton*, 2005]. If responsible, the observed 8‰ shift in $\delta^{13}C$ would suggest that CH_4 transport in tree tissue is more convective in nature, which is at odds with measured fluxes which indicate a slower turnover time. CH_4 oxidation in the rhizosphere, upper layers of soil, and potentially on the surfaces of the plant stems and leaves will enrich the isotopic composition of emitted CH_4 due to a significant kinetic isotope effect ($k_{12C}/k_{13C} \sim 1.025$) in aerobic bacterial CH_4 oxidation [*Raghoebarsing et al.*, 2005; *Tyler et al.*, 1994]. Under this mechanism, measurements of $\delta^{13}C$ above and below ground indicate that ~20% of CH_4 was oxidized in rice plots whereas 50–70% was oxidized in tree plots [*Tyler et al.*, 1997]. Finally, it is noteworthy that the average $\delta^{13}C$ of −54‰ emitted by trees is close to the $\delta^{13}C$ of CH_4 produced in aerobic environments of recent chamber studies involving whole C3 plants (−52‰) [*Keppler et al.*, 2006]. Thus, in future field studies it may not be possible to distinguish between aerobic and anaerobic mechanisms of CH_4 production based on the $\delta^{13}C$ of emitted CH_4 alone.

[16] Porewater CH_4 concentrations were found to be significantly lower in rice plots (mean 760 μg/L) than in either tree (mean 1570 μg/L) or control (mean 4960 μg/L) plots (Figure 2a) because of enhanced CH_4 transport from the rhizosphere to the atmosphere. In fact, average belowground CH_4 concentration was found to be inversely related to aboveground flux ($r^2 = 0.94$), supporting the assertion that transport was a controlling mechanism of belowground CH_4 concentrations. The isotopic composition of belowground CH_4 was found to be highly variable ($\delta^{13}C$ −63 to −48‰, Figure 2b) with no clear differences between species. The absence of a large $\delta^{13}C$ difference between rice and tree species belowground tends to favor the oxidative hypothesis for explaining the 8‰ difference in $\delta^{13}C$ of emitted CH_4. However, given the variability in belowground $\delta^{13}C$ and CH_4 concentration, more measurements will be necessary to verify this result.

[17] To determine if tree emissions have the potential to impact the global CH_4 budget, emissions were scaled using mean leaf area emission rate (0.7 ± 0.3 μg cm^{-2} hr^{-1}) across all broadleaf tree species in flooded environments from the Global Land Cover 2000 data set. The leaf area of the vegetation canopy from MODIS LAI in these regions during times of inundation was then used to scale the measured emissions. With this technique, global CH_4 emissions were estimated at 60 ± 20 Tg year^{-1}. Delineated spatially (Figure 3), the majority of CH_4 emissions (40 Tg) were in the tropical Amazon region of South America, the African Congo, and Indonesia. Significant emissions were also found in the northern mid to high-latitude regions of Eurasia (20 Tg). We note that these estimates assume belowground CH_4 concentrations similar to those in the greenhouse experiments, concentrations that may be higher than in natural settings by the amendment of organic matter [*Khalil et al.*, 2008].

[18] If this source of CH_4 is significant on the global scale as our bottom up approach suggests, it will have important implications for the pre-anthropogenic CH_4 budget. Recently, preindustrial atmospheric CH_4 was observed to be unexpectedly ^{13}C enriched based on an ice core record during the period 0–1300 AD ($\delta^{13}C \sim -47.5‰$), which may have resulted from enhanced biomass burning and a higher than previously considered geological CH_4 source [*Etiope et*

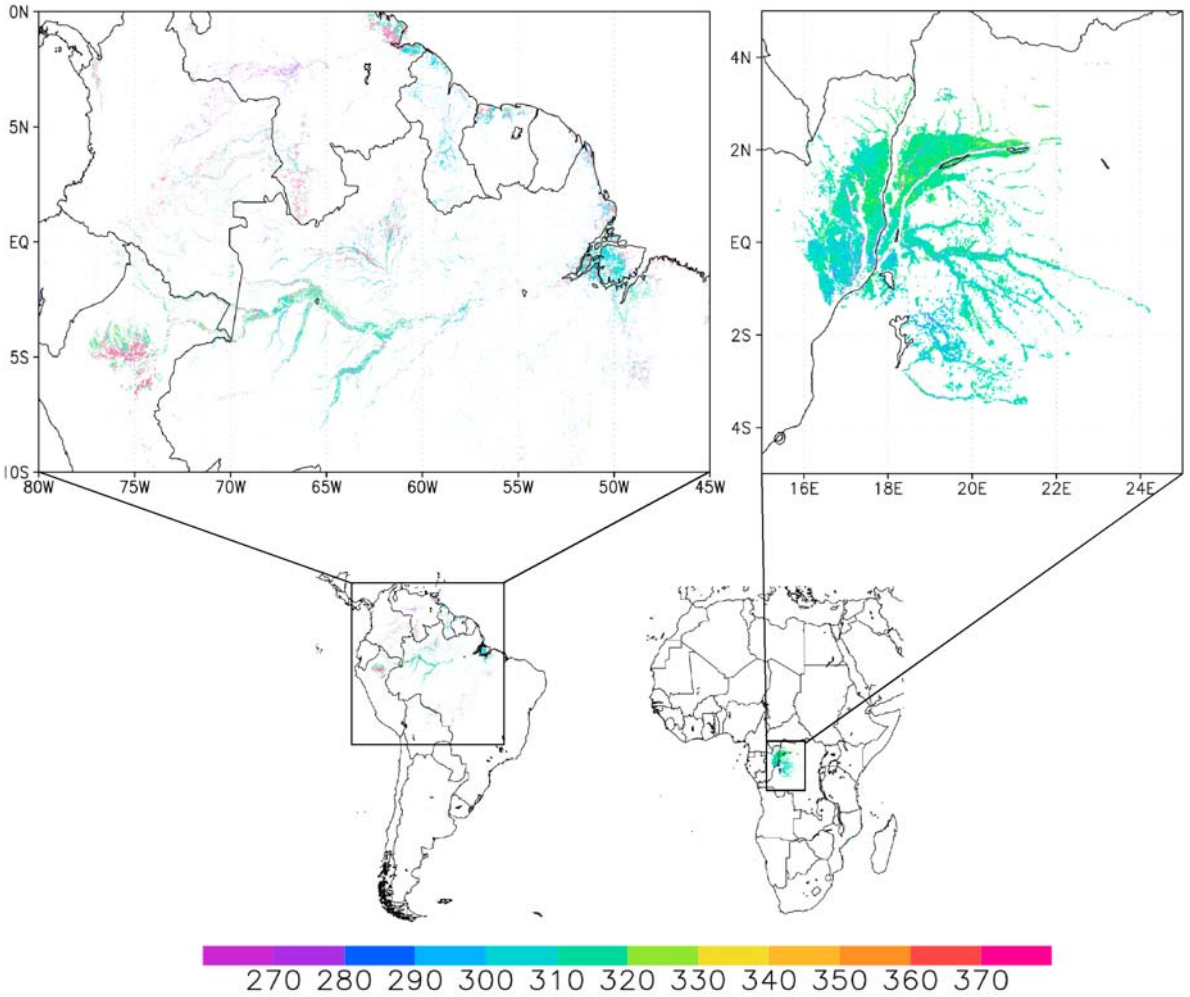

Figure 3. Emissions of CH_4 from trees scaled globally using the Collection 5 MODIS Leaf Area Index and the Global Land Cover 2000 product. Shown are CH_4 emissions from the tropical Amazon region of South America and the Congo Basin in Africa. Units are tons of CH_4 per year.

al., 2008; *Ferretti et al.*, 2005]. This compares with observations from ~1700 AD that are depleted in ^{13}C relative to modern CH_4 ($\delta^{13}C \sim -49‰$). Because trees appear to emit CH_4 enriched in $\delta^{13}C$ by ~8‰ compared with conventional wetland sources, this biogenic source can provide an alternative mechanism to shift the $\delta^{13}C$ of biogenic CH_4. To better constrain the tree source we employed a box model of the atmosphere that includes categories for biogenic, biomass burning, and geological sources for the preindustrial period 0–1700 AD (Table 1). The atmospheric kinetic isotope effect was estimated at −6 ± 1‰ [$(k_{13C}/k_{12C} - 1) \times 1000$] and assumed to be constant [*Lassey et al.*, 2007]. With CH_4 sources kept to lower estimates and source $\delta^{13}C$ values from the literature, we estimate the maximum global tree source strength to be 60 Tg (Table 1) [*Houweling et al.*, 2000; *Quay et al.*, 1999]. This global constraint coincides with the mean of bottom-up estimates of 60 ± 20 Tg year^{-1}.

4. Conclusions

[19] These results suggest that woody trees could present a sizeable global source of CH_4 to the budget, plausibly as large as 60 Tg yr^{-1}, and may help explain observed tropical enhancements in atmospheric CH_4 without a large aerobic plant source. Though we have confirmed the potential of such a source in our greenhouse mesocosm study and identified key regions that may represent significant sources of tree CH_4 emissions, field studies will be needed to confirm the magnitude and spatial distribution of this CH_4

Table 1. Global Emissions Strengths and Isotopic Compositions Used in the Box Model

	0–1000 AD	
	Strength (Tg yr^{-1})[a]	$\delta^{13}C$-CH_4 (‰)[a]
Wetland (conventional)	83	−60
Trees	60	−54
Termites	10	−60
Ocean	5	−40
Geological	5	−40
Biomass Burning	23	−20
Rice agriculture	5	−60
Ruminant Animals	20	−60
Total	211	−53

[a]Base budget for 0–1000 AD and isotopic signatures from previous work [*Houweling et al.*, 2000; *Quay et al.*, 1999].

source. Laboratory, greenhouse, and field studies across a wide variety of tree species (particularly tropical species) and grown in differing soil and water conditions would also be particularly useful to better characterize the variability in CH_4 emission rates. There are also several unanswered mechanistic issues including the pathway of conductance through the plant tissue to the atmosphere and the reason for the difference in $\delta^{13}C$ of emitted CH_4 between woody trees and herbaceous aquatic macrophytes.

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C. L. Butenhoff, M. A. K. Khalil, M. J. Shearer, A. L. Rice, and D. Teama, Department of Physics, Portland State University, Portland, OR 97207-0751, USA. (arice@pdx.edu)

T. N. Rosenstiel, Department of Biology, Portland State University, Portland, OR 97207-0751, USA.