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Landscape-level terrestrial methane flux observed from a very tall tower

Ankur R. Desai[a,*], Ke Xu[a], Hanqin Tian[b], Peter Weishampel[c], Jonathan Thom[a], Dan Baumann[d], Arlyn E. Andrews[e], Bruce D. Cook[f], Jennifer Y. King[g], Randall Kolka[h]

[a] *Center for Climatic Research, University of Wisconsin-Madison, Madison, WI, USA*
[b] *International Center for Climate and Global Change Research, Auburn University, Auburn, AL, USA*
[c] *Great Lakes Domain, National Ecological Observatory Network, Inc., Land O Lakes, WI, USA*
[d] *Wisconsin Water Science Center, U.S. Geological Survey, Rhinelander, WI, USA*
[e] *Earth Systems Research Lab, National Oceanographic and Atmospheric Administration, Boulder, CO, USA*
[f] *Goddard Space Flight Center, National Aeronautics and Space Administration, Greenbelt, MD, USA*
[g] *Department of Geography, University of California, Santa Barbara, CA, USA*
[h] *USDA Forest Service Northern Research Station, Grand Rapids, MN, USA*

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ABSTRACT

Simulating the magnitude and variability of terrestrial methane sources and sinks poses a challenge to ecosystem models because the biophysical and biogeochemical processes that lead to methane emissions from terrestrial and freshwater ecosystems are, by their nature, episodic and spatially disjunct. As a consequence, model predictions of regional methane emissions based on field campaigns from short eddy covariance towers or static chambers have large uncertainties, because measurements focused on a particular known source of methane emission will be biased compared to regional estimates with regards to magnitude, spatial scale, or frequency of these emissions. Given the relatively large importance of predicting future terrestrial methane fluxes for constraining future atmospheric methane growth rates, a clear need exists to reduce spatiotemporal uncertainties. In 2010, an Ameriflux tower (US-PFa) near Park Falls, WI, USA, was instrumented with closed-path methane flux measurements at 122 m above ground in a mixed wetland–upland landscape representative of the Great Lakes region. Two years of flux observations revealed an average annual methane (CH_4) efflux of 785 ± 75 mg C—CH_4 m^{-2} yr^{-1}, compared to a mean CO_2 sink of −80 g C—CO_2 m^{-2} yr^{-1}, a ratio of 1% in magnitude on a mole basis. Interannual variability in methane flux was 30% of the mean flux and driven by suppression of methane emissions during dry conditions in late summer 2012. Though relatively small, the magnitude of the methane source from the very tall tower measurements was mostly within the range previously measured using static chambers at nearby wetlands, but larger than a simple scaling of those fluxes to the tower footprint. Seasonal patterns in methane fluxes were similar to those simulated in the Dynamic Land Ecosystem Model (DLEM), but magnitude depends on model parameterization and input data, especially regarding wetland extent. The model was unable to simulate short-term (sub-weekly) variability. Temperature was found to be a stronger driver of regional CH_4 flux than moisture availability or net ecosystem production at the daily to monthly scale. Taken together, these results emphasize the multi-timescale dependence of drivers of regional methane flux and the importance of long, continuous time series for their characterization.

1. Introduction

The contribution of microbial methane (CH_4) from wetlands remains a significant source of uncertainty in closing the global methane budget (Mikaloff Fletcher et al., 2004). In particular, wetland methane emissions may contribute as much as 25–40% of global CH_4 anthropogenic emissions and are the leading source of interannual variability in atmospheric CH_4 (Bousquet et al., 2006; Chen and Prinn, 2006; Crill et al., 1993). The recent increase in the growth rate of atmospheric CH_4 lends particular urgency to improving global simulations and inversions of the terrestrial methane source (Chen and Prinn, 2006; Collins et al., 2006). One

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* Corresponding author. Tel: +1 608 520 0305; fax: +1 608 262 0166.
E-mail address: desai@aos.wisc.edu (A.R. Desai).

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set of hypothesized mechanisms is the role of warming of high latitudes and wetting of the tropics (Dlugokencky et al., 2009). Because CH_4 emissions are closely linked to changes in regional hydrology and temperature, and ongoing climate changes are likely to have a significant impact on regional water tables and wetland soil temperatures, there is a high likelihood that climate change will affect wetland CH_4 emissions (Roulet et al., 1992; Sulman et al., 2009).

Model results provide motivation for long-term in situ observations of terrestrial CH_4 sources and sinks. However, virtually all in situ measurements of surface to atmosphere CH_4 flux have been conducted either at the plot scale, typically with chamber-based measurements (e.g., Jungkunst and Fiedler, 2007), or more recently at the ecosystem scale, particularly with eddy covariance flux towers (e.g., Hatala et al., 2012). In contrast, atmospheric tracer-transport inversions (e.g., Bergamaschi et al., 2010; Miller et al., 2013), global ecosystem models (e.g., Matthews and Fung, 1987; Tang et al., 2010; Tian et al., 2010), and global remote sensing based estimates of CH_4 sources (e.g., Bloom et al., 2010) are provided at much larger spatial scales. Consequently, a scale mismatch arises for evaluation across methods. This scale mismatch is particularly difficult for CH_4 because of fine-scale spatial heterogeneity of CH_4 sources and sinks and sampling biases toward known CH_4 sources (e.g. peatlands).

The primary objective of this study is to evaluate the first very tall tower continuous eddy covariance flux measurement of CH_4 in a regional landscape. Further, we compared the magnitude and variability of these observations to plot-scale wetland and forest observations and model simulations. In late 2010, we instrumented a very tall tower in northern Wisconsin USA to observe CH_4 fluxes at 122 m above the ground and CH_4 concentration at 3 heights, sampling a spatially heterogeneous mix of upland forest and lowland wetland systems (Fig. 1). The site has been measuring CO_2 and H_2O eddy fluxes at this height and two others since 1996.

Since the pioneering studies using tunable diode laser spectroscopy-based eddy covariance for CH_4 fluxes (Fowler et al., 1995; Kim et al., 1998; Shurpali and Verma, 1998; Suyker et al., 1996), there have been a growing number of publications based on short-term CH_4 flux observations (e.g., Friborg et al., 2003; Hargreaves et al., 2001; Nicolini et al., 2013). With the development of reliable, low-drift, closed and open path methane analyzers (McDermitt et al., 2011), it is now possible to maintain long time series of CH_4 fluxes (e.g., Baldocchi et al., 2012; Hatala et al., 2012; Olson et al., 2013; Rinne et al., 2007; Smeets et al., 2009; Wille et al., 2008). None of these measurements have been made at the landscape scale (25–100 km^2) from a very tall tower, and only a subset of these studies report simultaneously on CH_4, CO_2, and H_2O flux measurements.

The value of continuous observations at landscape scales is to directly observe to what extent episodic and spatially heterogeneous emissions influence the net annual budget of biospheric CH_4 fluxes. Only continuous observations, for example, can regularly capture (or record) pulses of CH_4 (e.g., after a rainstorm or during ebullition events) (Strack and Waddington, 2008) along with non-growing season fluxes, which may also be substantial (Pelletier et al., 2007; Yu et al., 2007).

We seek to understand the nature of regional or landscape-scale net ecosystem exchange of CH_4 (NEE CH_4). In theory, we would expect that if wetland CH_4 production ($R_{\mathrm{eco\_CH_4}}$) dominates forest CH_4 consumption and wetland CH_4 oxidation, then the landscape CH_4 flux would be proportional to the wetland spatial extent and its mean flux as measured by chambers. Also, some ecosystem models simulate CH_4 production based on assuming a constant ratio of either ecosystem respiration (R_{eco}) to R_{eco} or NEE CO_2 to NEE CH_4 at annual timescales (e.g., Potter, 1997). To investigate these claims, we ask:

- What is the magnitude of NEE CH_4 in a mixed forest–wetland landscape and how does it compare to site-level chamber-based estimates?
- How predictive are environmental factors such as water table and temperature or other biogeochemical fluxes such as $R_{\mathrm{eco\_CH_2}}$ or NEE CO_2 on daily to interannual variability of NEE CH_4?
- How well does a state-of-the-art ecosystem model simulate landscape NEE CH_4?

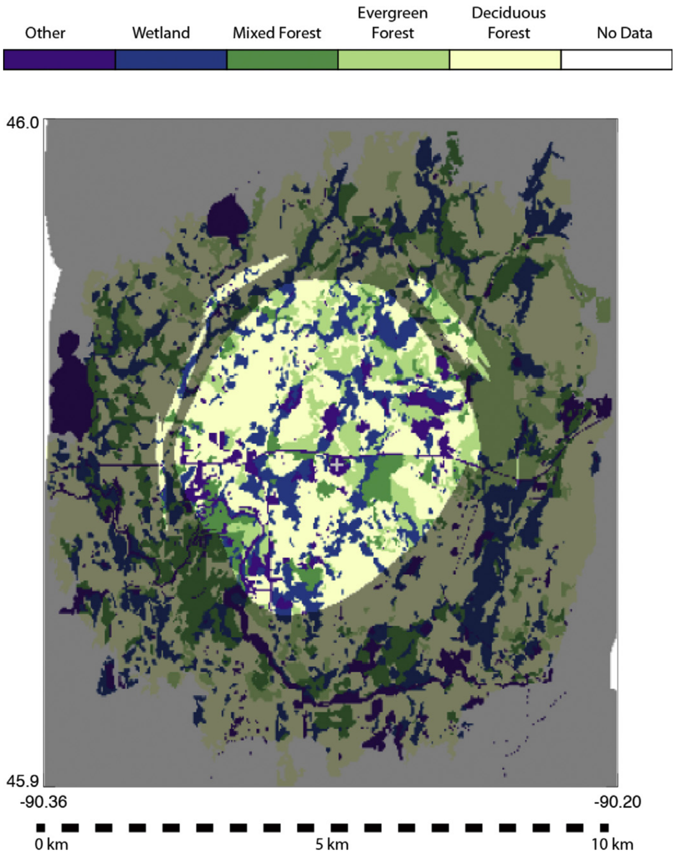

Fig. 1. Generalized land cover surrounding the WLEF Park Falls very tall tower (center cross) in a 10 km radius derived from manual classification of 30 m spatial resolution Quickbird imagery (B.D. Cook, unpublished data). "Other" category primarily includes grassy areas, lakes, and streams. Wetlands are patchy and equally distributed in all directions from tower. Footprint climatology overlaid as a mask, where lighter areas show >0.5% contribution to the May–Sept 2011 total hourly surface flux influence, revealing a typical footprint diameter of 5 km.

2. Methods

2.1. Site description

Methane flux and profile measurements were made at the WLEF very tall tower US-PFa Fluxnet site (Davis et al., 2003) in Wisconsin, USA (45.945°N, 90.273°W). The surrounding landscape (Fig. 1) is a representative mix of forested and open wetlands (28% in entire region (~50 km radius), 18% within 5 km radius of tower) with the remainder primarily composed of mixed deciduous and evergreen forests with most stands ranging from 30 to 70 years old. Most of the landscape is within the Chequamegon-Nicolet National Forest and forests that are actively managed for multiple purposes, including recreation, wildlife habitat, and timber production. Wetlands in the region include both open fens and forested bogs and a smaller proportion of open-water bodies. Upland stands are generally characterized by mixed northern hardwood species (*Acer saccharum*, *Tilia americana*, *Fraxinus pennsylvanica*, *Betula*