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A cool-temperate young larch plantation as a net methane source - A 4-year continuous hyperbolic relaxed eddy accumulation and chamber measurements

Masahito Ueyama[a,*], Kota Yoshikawa[a], Kentaro Takagi[b]

[a] Graduate School of Life and Environmental Sciences, Osaka Prefecture University, 599-8531, Japan
[b] Teshio Experimental Forest, Hokkaido University, Horonobe, 098-2943, Japan

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ABSTRACT

Upland forests are thought to be methane (CH_4) sinks due to oxidation by methanotrophs in aerobic soils. However, CH_4 budget for upland forests are not well quantified at the ecosystem scale, when possible CH_4 sources, such as small wet areas, exists in the ecosystem. Here, we quantified CH_4 fluxes in a cool-temperate larch plantation based on four-year continuous measurements using the hyperbolic relaxed eddy accumulation (HREA) method and dynamic closed chambers with a laser-based analyzer. After filling data gaps for half-hourly data using machine-learning-based regressions, we found that the forest acted as a net CH_4 source at the canopy scale: 30 ± 11 mg CH_4 m^{-2} yr^{-1} in 2014, 56 ± 8 mg CH_4 m^{-2} yr^{-1} in 2015, 154 ± 5 mg CH_4 m^{-2} yr^{-1} in 2016, and 132 ± 6 mg CH_4 m^{-2} yr^{-1} in 2017. Hotspot emissions from the edge of the pond could strongly contribute to the canopy-scale emissions. The magnitude of the hotspot emissions was 10–100 times greater than the order of the canopy-scale and chamber-based CH_4 fluxes at the dry soils. The high temperatures with wet conditions stimulated the hotspot emissions, and thus induced canopy-scale CH_4 emissions in the summer. Understanding and modeling the dynamics of hotspot emissions are important for quantifying CH_4 budgets of upland forests. Micrometeorological measurements at various forests are required for revisiting CH_4 budget of upland forests.

1. Introduction

Methane (CH_4) is the second most powerful anthropogenic greenhouse gas after carbon dioxide (CO_2). Atmospheric CH_4 concentration has risen to approximately 1860 ppb at year of 2016, which is more than 2.5 times relative to preindustrial levels (Intergovernmental Panel on Climate Change, 2013). The rising atmospheric CH_4 concentrations are determined by a balance between anthropogenic and natural sources and sinks by hydroxyl radical photochemical relation and upland soils (Kirschke et al., 2013). Due to limited measurements, the current understanding of the global CH_4 budget contains large uncertainties (Bridgham et al., 2013; Kai et al., 2011).

Uplands soils are estimated to be a sink of 9–47 Tg CH_4 yr^{-1} at the global scale (Kirschke et al., 2013). CH_4 is consumed by methanotrophs in soils under aerobic conditions. Previous measurements on upland soils showed that, in general, upland soils were sink of atmospheric CH_4 (Hashimoto et al., 2011; Morishita et al., 2007; Smith et al., 2000). Those measurements showed soil temperatures, air-filled porosity, and soil characteristics changed magnitude of CH_4 uptake, but generally did not change the direction from sink to source. Consequently, upland forests were modeled as a CH_4 sink due to their aerobic conditions (Curry, 2007; Ito and Inatomi, 2012).

CH_4 fluxes in upland forest floors were recently found to be considerably heterogeneous (Itoh et al., 2009; Miyama et al., 2011; Sakabe et al., 2016). Upscaling CH_4 fluxes using traditional chamber measurements suggested that CH_4 fluxes at the ecosystem scale differed from those at the chamber scale (Sakabe et al., 2016; Sundqvist et al., 2015b). Sakabe et al. (2016) showed that small hotspot emissions from anaerobic wet areas overwhelmed uptake at most unsaturated soils and turned CH_4 source at the watershed scale. To accurately estimate CH_4 budgets in upland soils, an ecosystem-scale understanding is required.

Micrometeorological CH_4 flux measurements—such as eddy covariance, flux-gradient relationship, and relaxed eddy accumulation methods—have been conducted in forest ecosystems in recent years due to the availability of laser-based analyzers (Sakabe et al., 2012; Shoemaker et al., 2014; Ueyama et al., 2013; Wang et al., 2013; Zenone et al., 2015). Consistent with chamber measurements, measured canopy-scale CH_4 fluxes showed a net sink at some upland forests (Smeets

* Corresponding author. Graduate School of Life and Environmental Sciences, Osaka Prefecture University, Sakai, Japan.
E-mail address: ueyama@envi.osakafu-u.ac.jp (M. Ueyama).

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et al., 2009; Ueyama et al., 2013; Wang et al., 2013). Conversely, micrometeorological measurements showed that some forests acted as a net CH_4 source at annual timescales or in particular periods (Querino et al., 2011; Sakabe et al., 2012; Shoemaker et al., 2014; Sundqvist et al., 2015a; Zenone et al., 2015). These measurements indicated that emissions from periodic wet areas contributed to the canopy-scale emissions (Sakabe et al., 2016; Sundqvist et al., 2015a; b), showing the importance of continuous monitoring for spatially representative CH_4 fluxes. Since the previous observations were limited to short periods less than few years (Querino et al., 2011; Sakabe et al., 2012; Shoemaker et al., 2014; Sundqvist et al., 2015a), interannual variabilities in ecosystem-scale CH_4 fluxes are not well understood.

In this study, we quantified the CH_4 budget at a cool-temperate larch plantation based on four-year continuous measurements using the hyperbolic relaxed eddy accumulation (HREA) method and dynamic closed chambers with a laser-based analyzer. We present the importance of the spatially representative measurements for evaluating CH_4 budget in forests, because hotspot emissions within a forest could contribute to the CH_4 budget at the canopy scale.

2. Field measurements

2.1. Study site

The study site was located inside the Teshio Experimental Forest of Hokkaido University in the northern part of Hokkaido island, Japan (Fig. 1; 45°03′N, 142°06′E, 66 m a.s.l.). In the study area, a mature forest was clear-cut from January to March 2003 and young larch saplings were planted at October 2003 for evaluating the effects of clear-cut harvesting and replanting on the CO_2 budget (Takagi et al., 2009; Aguilos et al., 2014). Before the clearcutting, dominant tree species were *Quercus crispula*, *Betula ermanii*, *Abies sachalinensis*, and *Betula platyphylla* with a dense understory of dwarf bamboos (*Sasa senanensis* and *Sasa kurilensis*). After the clearcutting, 2-year-old hybrid F1 larch (*Larix gmelinii* × *L. kaempferi*) saplings were planted. During the study period, the height of the overstory larch trees ranged from 5 to 7 m. The leaf area index measured by the plant canopy analyzer (LAI-2000, Li-Cor, USA) of the larch trees and the understory of the dwarf bamboos were 1.8 and 6.4 $m^2\,m^{-2}$ in the mid-summer, respectively. The soil was mainly a Gleyic Cambisol with approximately 10-cm thick organic horizon. Soil bulk density at 0- to 5-cm depth soils was $0.68 \pm 0.29\,g\,cm^{-3}$ (mean ± standard deviation randomly selected from 14 locations). The study area contained small hollows, ponds, and saturated soils, sporadically. Climate of the study area was classified as warm-summer humid continental climate (Dfb) by the Köppen climate classification. The mean annual air temperature was 5.9 °C from 2002 to 2010, with lowest and highest monthly means were observed in January or February (−7.3 °C) and August (19.0 °C), respectively. The average of the annual total precipitation was 1230 mm yr^{-1} during the period, where 33% of the precipitation was snowfall.

2.2. Measurements system

We developed the measurement system for the micrometeorological HREA, vertical concentration profile, and dynamic closed chambers using a laser-based greenhouse gas analyzer (FGGA-24r-EP, Los Gatos Research Inc., USA). We chose the HREA method, because the method allows continuous flux measurements with a low power consumption due to its applicability at slow flow rates (Businger and Oncley, 1990), and increases detection limit for measuring small fluxes (Bowling et al., 1999). The gas analyzer measured CH_4, CO_2, and water vapor concentration, simultaneously. The measurement system was based on our previous measurement systems for the HREA and vertical concentration profile measurements (Ueyama et al., 2013, 2014) and the chamber measurements (Ueyama et al., 2015), but combined the two systems. The system measured micrometeorological CO_2 and CH_4 fluxes, storage, and chamber-based soil fluxes by correcting the water vapor dilution effect. Our measurement systems were intensively tested at various forest ecosystems (Hamotani et al., 2001; Ueyama et al., 2009, 2012; 2013; Sakabe et al., 2012). Details for the system were shown in previous studies (Ueyama et al., 2013, 2014, 2015), but we briefly describe the system as follows.

The sampling system was fully controlled by a data logger at 10 Hz (CR1000, Campbell Scientific Inc., USA) with two extended relay control modules (SDM-CD16S and SDM-CD16AC, Campbell Scientific Inc., USA). The air flow was switched using solenoid valves (USB3-6-2-E and USG3-6-2-E, CKD Corp., Japan). The sampling schedule is shown in Table A1.

2.2.1. Hyperbolic relaxed eddy accumulation system

For the HREA method, the inlets for updraft and downdraft sampling were installed approximately 0.19 m from the sonic anemometer (DA600-3TV, Sonic Co., Japan). Updrafts and downdrafts were sampled through aluminum-coated polymer tubes (4 mm inner diameter; DK

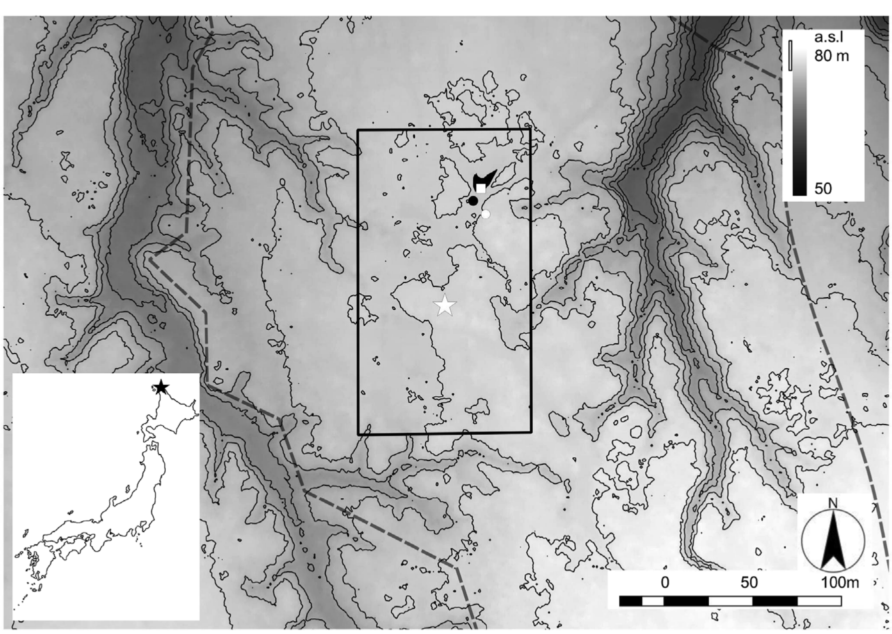

Fig. 1. Map of the study site. Solid rectangular and thick broken lines show the plot for the soil water content survey (see Fig. A2) and boundary of the plantation, respectively. Flux tower, chamber 1-2, 3, and 4 are shown by an open star, open circle, closed circle, and open square, respectively. Black area behind the open square is a permanent pond. Elevation is shown as a black (lower)–white (higher) gradation and thin contour lines drawn every 2 m in height.