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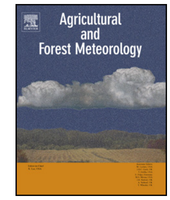

Ecosystem scale methane fluxes in a natural temperate bog-pine forest in southern Germany

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ABSTRACT

Methane (CH_4) and carbon dioxide (CO_2) exchange were investigated over 15 months above a natural bog-pine site in the pre-alpine region of southern Germany. The measurements indicate annual methane emissions of $+5.3 \pm 0.34\,g\,C\,m^{-2}\,a^{-1}$ and an annual CO_2 uptake of $-62 \pm 20\,g\,C\,m^{-2}\,a^{-1}$, resulting in a global warming potential balance of $-50 \pm 74\,g\,[CO_2\ eq.]\,m^{-2}\,a^{-1}$. Air temperature was identified as the environmental parameter showing the highest correlation with methane production, except for periods with low water table (<−0.12 m). Furthermore, we compared three different methane flux gap-filling methods: the mean daily variation approach (MDV), a look up table (LUT) with various control parameters and an exponential regression function between methane flux and air temperature (NLR). It turns out that the LUT provides the best result for the gap-filling of half-hourly CH_4 fluxes for the present data. By increasing the number of parameters in the LUT, the CH_4 flux prediction could be considerably improved. Except for dry periods, day to day variations could be reproduced very well by the NLR method, but results for sub-daily fluctuations were poor. The choice of gap-filling method affects the annual methane budget estimate by at most $\pm 0.5\,g\,C\,m^{-2}\,a^{-1}$, or about 10% of the annual flux.

This study presents one of the first eddy covariance based annual methane- and CO_2-exchange estimates over a natural bog-pine ecosystem outside the boreal zone.

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1. Introduction

Pristine peatlands are characterized by water saturated soil conditions, leading to suppressed organic matter decomposition. In undisturbed peatlands, plant assimilation generally exceeds soil respiration, and atmospheric carbon dioxide (CO_2) is fixed as biomass into the accumulating peat. Natural peatland ecosystems are commonly considered to be moderate sinks of atmospheric CO_2. Reported annual net ecosystem exchange of CO_2 (NEE) of bogs in the Northern Hemisphere mostly range between −15 and $-80\,g\,C\,m^{-2}\,a^{-1}$ (e.g. Hommeltenberg et al., 2014; Lund et al., 2007; Saarnio et al., 2007; Sottocornola and Kiely, 2005). On the other hand, anaerobic soil conditions in natural peatlands support the formation of methane (CH_4), which is a potent greenhouse gas. It is 25 times stronger compared to CO_2, in a 100 years' time horizon, and is estimated to be responsible for about 20% of current radiative forcing (IPCC Climate Change, 2007). Wetlands contribute about 20–25% to current global methane emissions, (total of $115–227\,Tg\,CH_4\,a^{-1}$; Bergamaschi et al., 2007; Bloom et al., 2010; Lelieveld et al., 1998) and thus constitute the single largest natural emission source-type of methane worldwide (Bridgham et al., 2013).

Methane emissions exhibit high variations across peatland types (Lai, 2009) and other land use forms (Byrne et al., 2004; Hendriks et al., 2010). In the last two decades, several measurement approaches, such as static chambers (e.g., Beetz et al., 2013; Drösler, 2005; Moore and Knowles, 1990; Moore et al., 2011), automatic chambers (e.g., Bäckstrand et al., 2010; Bubier et al., 2003), flux gradient techniques (e.g., Edwards et al., 2001; Miyata et al., 2000; Simpson et al., 1997) and eddy covariance measurements (e.g., Baldocchi et al., 2012; Herbst et al., 2011; Rinne et al., 2007), have been used to estimate the net ecosystem methane production (NEMP) over different peatland types. Although there is much experience of CO_2- and water vapor-exchange measurements by

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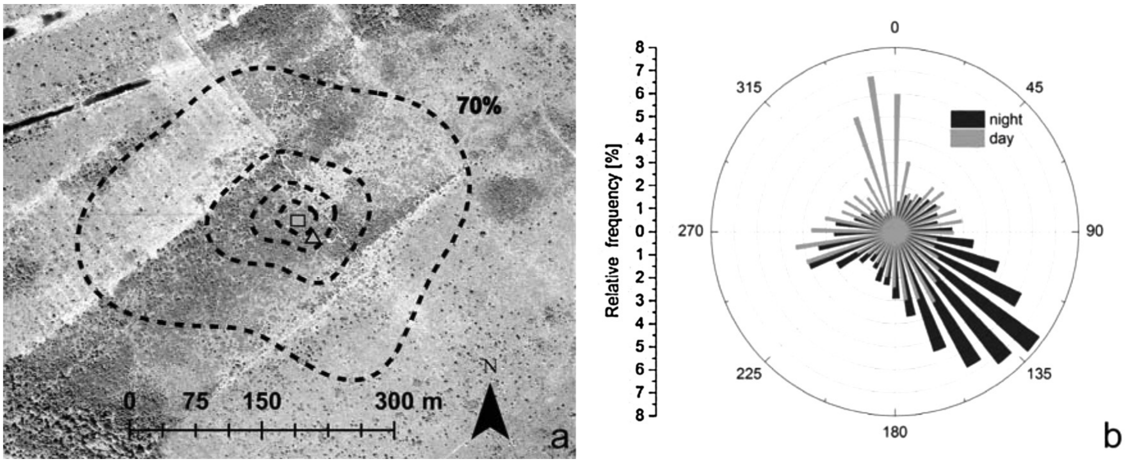

Fig. 1. (a) Aerial image of the Schechenfilz site (based on Google maps). Dark gray: bog pines; light gray: open bog area (grassland and dwarf shrubs); black dashed lines: mean footprint isolines (10%, 30%, 50% and 70%, estimated following Kormann and Meixner (2001) over one year (July 2012–June 2013). The square marks the main eddy covariance tower (CH_4, CO_2 and H_2O fluxes). The triangle marks a second tower (CO_2 and H_2O fluxes and auxiliary environmental parameters); (b) distribution of wind directions over one year (July 2012–June 2013), in 10° bins. Data are separated in day and nighttime (threshold of 20 W m^{-2}). Gray bars: daytime; black bars: nighttime.

the eddy covariance technique, some details of determining annual CH_4 balances are still rarely discussed. For example, the effect of different gap-filling methods on annual methane flux estimates has not been reported yet, to our knowledge. Experiences based on CO_2 gap-filling cannot be simply transferred to CH_4 gap-filling, since the main environmental factors controlling CH_4 exchange differ from the main drivers of CO_2 exchange, which are commonly photosynthetic photon flux density (PPFD) and temperature (e.g., Flanagan et al., 2002; Law et al., 2002; Schmid et al., 2003). Reported main environmental drivers of CH_4 exchange include water table depth (e.g., Bubier et al., 1993; Parmentier et al., 2011; Pelletier et al., 2007; Roulet et al., 1992) and soil temperature (e.g., Hargreaves et al., 2001; Rinne et al., 2007; Wille et al., 2008), as well as the presence of cattle in the flux footprint (e.g., Baldocchi et al., 2012; Herbst et al., 2011). Additionally, primary productivity and substrate availability (e.g., Bergman et al., 2000; Friborg et al., 2000; Nykanen et al., 2003; Whiting and Chanton, 1993) and atmospheric turbulence transport (Wille et al., 2008) are also suspected to affect methane emissions. The relative importance of these main drivers is often not consistent during the annual cycle (Herbst et al., 2011; Rinne et al., 2007), or are related to the specific ecosystem and site management. Furthermore, reported data on emission factors of methane and their influencing parameters are sparse for many ecosystem types. For example, comprehensive knowledge about the full greenhouse gas exchange of peatland forests is still lacking (Maljanen et al., 2010).

In this study, we present the CH_4 and CO_2 balance of one measurement year of a natural, temperate bog-pine forest site in southern Germany. As N_2O fluxes are assumed to be negligible at natural and nutrient poor peatland sites (Laine et al., 1996; Laurila et al., 2012), we can thus examine the total greenhouse gas balance of one complete annual cycle. Furthermore, we compared gap-filling methods, to get the best correlation between measured and modeled CH_4 fluxes at our site. The comparison included three different approaches: the mean daily variation (MDV), look up table (LUT) and non-linear regression between methane and temperature (NLR), in analogy to the CO_2 gap-filling methods comparison discussed by Falge et al. (2001).

2. Study site and methods

2.1. Site description

Measurements of methane and carbon dioxide exchange were performed over 15 months, between July 2012 and September 2013, at a bog forest site called "Schechenfilz" in the pre-alpine region of southern Germany (47°48′23.22″N and 11°19′41.31″E, 590 m a.s.l. see also Hommeltenberg et al., 2014). Schechenfilz is part of the TERENO pre-Alps observatory (Zacharias et al., 2011), and a future site of the European Integrated Carbon Observation System (ICOS, www.icos-infrastructure.eu).

In the central part of the flux footprint (Fig. 1a) vegetation is dominated by slow growing bog-pines (*Pinus mugo* ssp. *rotundata* (Link)) with an average canopy height of 2 m and a mean plant area index (PAI) of 2.3 ± 0.8, estimated by 100 individual measurements of a SunScan Canopy Analysis System (SS1, Delta-T, Cambridge, UK). The ground layer vegetation is dominantly formed by peat mosses (*Sphagnum* spp.), augmented by heather (*Calluna vulgaris* (L.)), bog-bilberry (*Vaccinium uliginosum* (L. s. l)), and species of the sedge-family (mainly *Eriophorum vaginatum* (L.)). In the research area, the peat layer is still pristine and about 5.1 m thick.

The wind system at Schechenfilz is subjected to the lake breeze phenomenon (Fig. 1b), caused by a large lake (Lake Starnberg) around 2 km north of the site. Thus, the dominant wind direction is north–west during daytime and south–east during nighttime. The site is located within the temperate and humid climate zone (Köppen–Geiger climate classification, e.g. Kottek et al., 2006). The long-term average of air temperature is 8.6 °C and the mean annual precipitation is 1127 mm (data provided by the nearby climate station "Attenkam" of the German weather service (DWD)). Three years of water table (WT) measurements suggest an average level of −0.05 ± 0.05 m below the surface, ranging between +0.07 and −0.32 m.

2.2. Eddy covariance (EC) method and instrumentation

Fluxes of CH_4 and CO_2 were calculated using the eddy covariance method (e.g. Aubinet et al., 2000; Baldocchi et al., 1988; Foken et al., 2012a), which derives turbulent fluxes of scalars using high frequency measurement systems. The eddy-flux of any scalar c (e.g. CH_4) can be expressed as:

$$F_c = \overline{w'c'} = \frac{1}{n}\sum_{i=1}^{n}\left[(c_i - \overline{c}) \times (w_i - \overline{w})\right], \quad (1)$$

where c' is the deviation from the mean concentration $\overline{c}$ of a scalar c. c_i is the measured concentration of the scalar and w_i is the vertical wind speed in m s^{-1}. The number n depends on the measurement frequency and the averaging period.

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