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Methane emissions in Danish riparian wetlands: Ecosystem comparison and pursuit of vegetation indexes as predictive tools

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ABSTRACT

The present study was conducted to (i) investigate parameters influencing the fluxes of the greenhouse gas methane (CH_4) in Danish riparian wetlands with contrasting vegetation characteristics and (ii) develop models relating CH_4 emissions to soil and/or vegetation parameters integrating the spatial and temporal variability in the fluxes. Fluxes of CH_4 were monitored in 12 wetland plots over a year using static chambers, yielding a dataset with more than 800 measured fluxes of CH_4. Yearly emissions of CH_4 ranged from −0.2 to 38.3 g CH_4-C m^{-2} $year^{-1}$, and significant effects of groundwater level, soil temperature (10 cm depth), peat depth, sulfate, nitrate, and soil carbon content were found. Two methods based on easily available environmental parameters to estimate yearly CH_4 emissions from riparian wetlands are presented. The first uses a generalized linear model (GLM) to predict yearly CH_4 emissions based on the humidity preference of vegetation (Ellenberg-F), peat depth and degree of humification of the peat (von Post index). The second method relies solely on plant species composition and uses weighted-average regression and calibration to link the vegetation assemblage to yearly CH_4 emission. Both models gave reliable predictions of the yearly CH_4 fluxes in riparian wetlands (modeling efficiency > 0.35). Our findings support the use of vegetation, possibly in combination with some soil parameters such as peat depth, as indicator of CH_4 emission in wetlands.

1. Introduction

Riparian wetlands are ecotones located at the boundary between terrestrial and aquatic environments and, in their natural state, often exhibit high biodiversity (Naiman and Decamps, 1997; Tockner and Stanford, 2002; Ward et al., 1999). Riparian wetlands are also biogeochemical hotspots due to the close interaction between soil and water (McClain et al., 2003) and they have the potential to filter and transform various waterborne pollutants before they enter the aquatic ecosystems (Vidon, 2010).

However, wetlands constitute the largest natural source of methane (CH_4), which is a greenhouse gas (GHG) valued as 25 times the global warming potential (GWP) of CO_2 (IPCC, 2007). Methane is produced by methanogenic archaea as a result of fermentation of organic compounds, such as acetate, or reduction of CO_2 by H_2 (Le Mer and Roger, 2001). Methanogenesis requires strictly anaerobic conditions and might be inhibited in the presence of other electron acceptors such as nitrate (NO_3^-), iron (Fe(III)) or sulfate (SO_4^{2-}) (Le Mer and Roger, 2001). During convective flow or diffusive transport toward the surface, the CH_4 produced in the deeper anaerobic zones of wetlands can be oxidized to CO_2 by methanotrophic bacteria in aerobic soil layers, thus limiting the amount of CH_4 emitted to the atmosphere (Le Mer and Roger, 2001; Whalen, 2005).

Despite the acknowledged potential of wetlands in emitting CH_4, the number of studies quantifying annual GHG emissions from riparian wetlands is limited as monitoring is labor intensive (e.g. chamber method) and expensive (e.g. eddy covariance technique) (Couwenberg et al., 2011; Joosten and Couwenberg, 2009). Methane emissions from riparian wetlands are highly variable (Saarnio et al., 2009). Thus, emission rates ranging from 0.09 to 68 g CH_4-C m^{-2} $year^{-1}$ have been reported for European freshwater marshes and minerotrophic mires (Saarnio et al., 2009), and even higher rates have been recorded at a riverside in Ohio, USA (379 g CH_4-C m^{-2} $year^{-1}$; Sha et al., 2011). The main controllers of CH_4 emission were found to be groundwater level (GWL), temperature and carbon availability (Le Mer and Roger, 2001), but temporal fluctuation in these parameters, especially in water level and temperature, implies that long term monitoring (i.e. minimum

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one year) is needed to provide reliable estimates of CH_4 fluxes. Furthermore, spatial extrapolation of the results can be difficult, particularly because the water level can show large spatial variation due to the micro-topography often encountered in wetlands such as hummocks and hollows. Therefore, there is a need for predictors integrating the spatial and temporal variability of parameters influencing CH_4 emission to obtain reliable CH_4 emission estimates.

Some studies have pointed out that vegetation may potentially be used as a proxy for CH_4 emission (Bubier et al., 1995; Couwenberg et al., 2011; Dias et al., 2010). These studies make the assumption that the drivers affecting the vegetation are similar to those controlling CH_4 emission. Indeed, GWL has been demonstrated to be the main driver of wetland CH_4 emissions (see e.g. Couwenberg et al., 2011; Pelletier et al., 2007; Salm et al., 2011) and also affects plant species composition (Ellenberg et al., 1992; Schaffers and Sýkora, 2000). However, the link between vegetation and CH_4 fluxes can also be direct as vegetation via root exudates provides organic matter that can be hydrolysed, fermented and ultimately used by methanogens (Schäfer et al., 2012). Additionally, CH_4 transport in aerenchymatous plant species can create a shortcut between the soil anoxic zone and the atmosphere and, consequently, increase the emission of CH_4 that could otherwise be oxidized in the upper oxic soil layers (Le Mer and Roger, 2001).

In order to study the parameters influencing the emission of GHG in riparian wetlands and explore the use of vegetation as a predictor of CH_4 emissions, we monitored over a full year the fluxes of CH_4 in four Danish riparian wetlands, each comprising three plots presenting contrasting vegetation types. We investigated how differences in soil, water and vegetation characteristics among plots affected the fluxes of CH_4. Further, we attempted to develop estimators of the yearly emission of CH_4 by use of simple predictive models based on environmental variables and including ecophysiological vegetation indices.

2. Materials and methods

2.1. Study sites

The four riparian wetlands studied were located along four medium-sized naturally meandering streams: River Karup (N 56.417°, E 9.002°), River Haderup (N 56.404°, E 9.009°), River Simested (N 56.687°, E 9.484°) and River Villestrup (N 56.739°, E 9.958°) (Fig. 1). The wetlands were situated in the two main geo-regions of Denmark: the outwash plains of western Denmark (Karup and Haderup) and the moraine landscape of eastern Denmark (Simested and Villestrup). These two regions are geochemically contrasting as the western region includes areas rich in pyrite (FeS_2), whereas the eastern region, formed during the last glaciation (Weichsel), has higher calcium contents (Petersen et al., 2012). The sites were all located in catchments dominated by agricultural land use representing 61% (Karup), 51% (Haderup), 82% (Simested) and 46% (Villestrup) of the total upland river catchment area at the study sites.

The studied areas are some of the least disturbed wetland sites in Denmark (Baattrup-Pedersen et al., 2013). Within each wetland site, three ca. 25 m^2 plots (P1, P2 and P3) with contrasting types of vegetation were selected comprising, for example, tall reed beds, meadows and protected rich fens. The vegetation inside the plots was neither mowed nor grazed during the study period. The plots were all located within 100 m from the stream channel and most could be inundated in periods with high stream discharges, although no inundations occurred during the study period (June 2010–June 2011). At each plot, four sub-plots (55 cm × 55 cm) were established in order to cover the heterogeneities in vegetation composition within the plots. The main characteristics of the plots are given in Table 1. Plot 1 at Karup was located at the bottom of a hill and was constantly fed by groundwater coming from an agricultural catchment, and Karup P2 and P3 were both located inside a meander of the River Karup and had high GWL throughout the study period. Plot 1 at Haderup had constantly high GWL, while it was more fluctuating at P2 and drier at P3. The riparian area of the River Simested was grazed by cattle and the upland area consisted of agricultural fields under crop rotation. Simested P1 had upwelling groundwater flow and the GWL was thus constantly high, while Simested P2 and P3 had lower GWL. The Villestrup wetland was fertilized and grazed and located along the River Villestrup in a forested catchment. Villestrup P1 had high GWL, whereas P2 and P3 had lower GWL. Precipitation and average air temperature for the four sites are given in Table 2.

Fig. 1. Map of Denmark showing the locations of the four wetlands studied.

2.2. Soil characteristics

At each plot, two undisturbed volumetric soil cores were sampled at 0–30 cm depth in summer 2010 with a liner sampler (04.15.SB, Eijkelkamp, NL) within a distance of ca. 5 m from the sub-plots, and bulk density was determined after drying one of the soil cores at 105 °C. Soil pH was measured in the field directly in one of the wet soil cores using a field pH meter (HACH HQ11d) and a field electrode (Radiometer pH C2051-8). The second soil core was used for chemical analysis. After drying (60 °C) and ground milling, total organic carbon (TOC) and total nitrogen (TN) were determined by dry combustion (elemental analysis) at AGROLAB GmbH, Germany, using the international standards ISO10694:1995(E) and ISO 13878:1998(E). The soil content of Fe(III) available for microbial reduction was determined as oxalate extractable iron (Fe_{ox}) using the procedure described by Schoumans (2000). Content of Fe in the oxalate extract was determined by ICP-OES (Varian 725-ES, 238.204 nm, AGROLAB GmbH, Germany). Results of C, N and Fe_{ox} were corrected for water content at 60 °C and reported as mass per dry weight (as determined at 105 °C).