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Upscaling of methane exchange in a boreal forest using soil chamber measurements and high-resolution LiDAR elevation data

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ABSTRACT

Forest soils are generally considered to be net sinks of methane (CH_4), but CH_4 fluxes vary spatially depending on soil conditions. Measuring CH_4 exchange with chambers, which are commonly used for this purpose, might not result in representative fluxes at site scale. Appropriate methods for upscaling CH_4 fluxes from point measurements to site scale are therefore needed. At the boreal forest research site, Norunda, chamber measurements of soils and vegetation indicate that the site is a net sink of CH_4, while tower gradient measurements indicate that the site is a net source of CH_4. We investigated the discrepancy between chamber and tower gradient measurements by upscaling soil CH_4 exchange to a 100 ha area based on an empirical model derived from chamber measurements of CH_4 exchange and measurements of soil moisture, soil temperature and water table depth. A digital elevation model (DEM) derived from high-resolution airborne Light Detection and Ranging (LiDAR) data was used to generate gridded water table depth and soil moisture data of the study area as input data for the upscaling. Despite the simplistic approach, modeled fluxes were significantly correlated to four out of five chambers with $R > 0.68$. The upscaling resulted in a net soil sink of CH_4 of $-10\,\mu mol\,m^{-2}\,h^{-1}$, averaged over the entire study area and time period (June–September, 2010). Our findings suggest that additional contributions from CH_4 soil sources outside the upscaling study area and possibly CH_4 emissions from vegetation could explain the net emissions measured by tower gradient measurements.

1. Introduction

The only well characterized biospheric sink for CH_4 is oxidation by methanotrophic bacteria in soil (Harriss et al., 1982). Globally, this soil CH_4 sink was estimated to range between 28 and 32 Tg CH_4 yr^{-1}, which amounts to around 5% of the destruction of CH_4 by OH radicals in the troposphere (Kirschke, 2013). Forest soils are generally considered to be net sinks of CH_4 with higher uptake rates than grassland and arable land (Boeckx et al., 1997; Dutaur and Verchot, 2007). However, CH_4 production by archeans usually dominates in anaerobic forest soil environments such as waterlogged soils (Christiansen et al., 2012; Jungkunst et al., 2008; McNamara et al., 2006). CH_4 production also takes place in well-aerated soils at anaerobic micro sites (Fischer and Hedin, 2002; Kammann et al., 2009) and in deeper soil layers where anaerobic conditions occur (Kammann et al., 2001). Hence consumption and production can occur simultaneously at one location and soil conditions will determine the direction of the net flux. Vegetation might also contribute to the CH_4 exchange of a forest. Trees have been found to transport CH_4 originating from soil water and to release it through the stem or foliage (Terazawa et al., 2007; Gauci et al., 2010). Aerobic formation of CH_4 in green plants has also been observed (Keppler et al., 2006; Vigano et al., 2008), although the mechanisms governing plant CH_4 release are still discussed (Bruhn et al., 2012) and there is little evidence of plant emissions of CH_4 from in situ studies (Sundqvist et al., 2012). On the contrary, Sundqvist et al. (2012) found evidence for plant uptake of atmospheric CH_4 from measurements on spruce, pine, birch and rowan in a boreal forest.

Soil CH_4 flux rates also vary considerably both spatially and temporally (Christiansen et al., 2012; Ishizuka et al., 2009; Konda et al., 2008; Lessard et al., 1994; Reay et al., 2005; Yu et al., 2008). Spatial variability in soil CH_4 fluxes can be due to variability in soil moisture, soil texture, and water table depths, factors that are

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dependent on topography, vegetation, and soil type, for example. Soil moisture (Castro et al., 1994; Guckland et al., 2009; Lessard et al., 1994) and soil texture (Dorr et al., 1993; Dutaur and Verchot, 2007; Ishizuka et al., 2009) alter soil diffusivity, which controls the rate at which atmospheric CH_4, and oxygen are supplied to the bacteria. Water table depth alters the relative extent of aerobic and anaerobic zones in soils. A rise of the water table leads to a decreased oxic soil zone and thus reduced CH_4 uptake (Kammann et al., 2001; Roulet et al., 1992). Changes in soil temperature and precipitation are also responsible for temporal variability in CH_4 exchange. Increases in temperature stimulate the activity of both methanogens (Yvon-Durocher et al., 2014) and methanotrophs (Crill et al., 1994; King and Adamsen, 1992), although methanogens benefit more (Dunfield et al., 1993). Other factors that have been found to influence soil CH_4 exchange in forests are soil pH (Weslien et al., 2009) and nitrogen availability (Steudler et al., 1989).

In situ chamber measurements and soil incubations in laboratories have long been the dominant methods for studying CH_4 exchange in forests, although larger scale micrometeorological methods are gaining in popularity (Nicoloni et al., 2013). While CH_4 exchange occurs and is often measured at the centimeter scale, it varies globally, and has a significant influence on biospheric–atmospheric interactions and feedbacks associated with climatic change (Schimel and Potter, 1995). Appropriate upscaling of CH_4 exchange from chamber-based point measurements will allow scientists to better understand the contribution of methane from soil and plant environments measured using eddy covariance/micrometeorological methods with extension to model estimates of regional to global CH_4 budgets (Hashimoto et al., 2011; Marushchak et al., 2013; Schimel and Potter, 1995). A few studies have upscaled CH_4 fluxes using simple extrapolations of chamber measurements or soil incubations from a few locations multiplied by site area. However these methods do not consider the spatial heterogeneity of forest soil texture or type, or topographical variability, which may greatly influence wetting and drying regimes, and therefore CH_4 fluxes.

Global and regional estimates of soil CH_4 sink strength use soil texture classes (Dorr et al., 1993; Dutaur and Verchot, 2007), land use type (Grunwald et al., 2012), ecosystem class and/or climatic zones (Dutaur and Verchot, 2007) to spatially parameterize CH_4 exchanges. However, regional models often fail to incorporate the spatial heterogeneity within each class, including fuzzy boundaries between classes. This results in inaccurate characterization of classes, and especially within the sometimes broad transition zones between classes (Matson et al., 1989). These issues may be overcome by incorporating process-based models of CH_4 consumption driven by gaseous diffusion or diffusion in combination with microbial activity (Curry, 2007; Del Grosso et al., 2000; Ridgwell et al., 1999). Some process-based models do not account for production of CH_4 and are not applicable to soils that seasonally shift from net sinks to net sources (Del Grosso et al., 2000). Process-based models can become exceedingly complex, requiring detailed inputs of spatio-temporally varying climate, vegetation and soil physiochemical properties (Hashimoto et al., 2011). More simple, empirical models have been developed for site-specific applications. Castro et al. (1994) found that soil moisture, as the only explanatory variable, could satisfactorily predict CH_4 fluxes at locations within a temperate forest. Christiansen et al. (2012) used spatial variability in soil moisture and water table depths derived from elevation data to upscale CH_4 fluxes from manual chamber measurements to site scale at two temperate deciduous forests.

At the Norunda boreal forest site in central Sweden, chamber measurements of soils and vegetation indicate that the site is a net sink of CH_4 (Sundqvist et al., 2012, 2014), while gradient measurements above the forest canopy indicate that the site is a net source of CH_4 (Sundqvist et al., 2015). The aim of this study was to quantify soil CH_4 exchange for the entire site (100 ha) by upscaling soil CH_4 exchange through developing an empirical model for a mature coniferous forest based on automated chamber observations with a high temporal resolution, in combination with high-resolution LiDAR elevation data. The model will also serve as a mean to further examine the discrepancy between results obtained from chamber measurements and tower gradient measurements. In correspondence to findings of Christiansen et al. (2012), Fiedler et al. (2005) and Grunwald et al. (2012), we hypothesize that emissions from wet patches scattered at the site may exceed the uptake in well-aerated parts of the soil and hence even relatively small source areas may shift a larger area from a sink to a source (Fiedler et al., 2005).

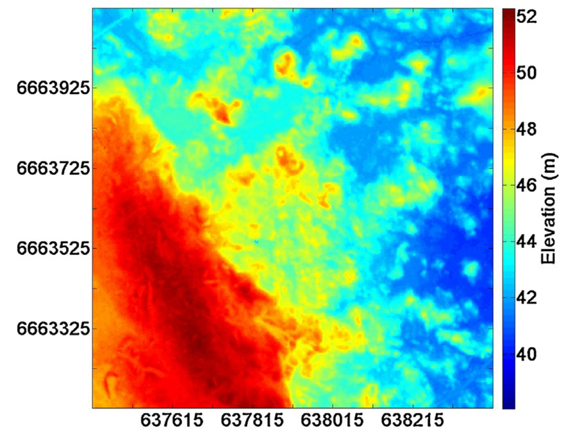

Fig. 1. Digital Elevation Model (DEM) of the study area. Coordinates are given in UTM (WGS 84).

2. Method

2.1. Site description

Upscaling of soil CH_4 exchange was completed for a 100 ha area at the Norunda site, 60°5′ N, 17°29′ E, in central Sweden from July through September 2010 during coincident chamber and tower gradient measurements. The Norunda site is situated at the southern edge of the boreal forest zone and is comprised of 120 years old mixed pine (*Pinus sylvestris*) and spruce (*Picea abies*) trees. The forest was thinned in 2008 within the NE to SW sectors surrounding the measurement tower to a radius of 200 m, which decreased the leaf area index within this area from 4.8 to 2.8 $m^2 m^{-2}$. Trees within the SW to NE sectors have not been thinned nor fertilized in the last few decades. Soil are comprised of glacial till, classified as dystric regosol (Lundin et al., 1999) and include an organic layer of about 3–10 cm. The area within 500 m radius of the measurement tower is relatively flat, with elevation ranges from 40 to 52 m above sea level (Fig. 1). Since 1843, the water table in the area has been artificially lowered as a result of several ditches surrounding the forest. The last known ditch installation was in 1980. Mean air temperature measured at Uppsala climate station, 30 km south of Norunda, was 6.5 °C and mean precipitation was 576 mm (1980–2010).

2.2. Instrumentation

In this study, eight CH_4 chambers are used: three chambers (T1–T3) were located in the thinned section, and five (U1–U5) were located in the undisturbed section of the forest. In areas of higher water table, CH_4 exchanges were measured, using a single 'floating' chamber positioned on standing shallow water in the thinned section of the forest.