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# Reconstruction of Holocene carbon dynamics in a large boreal peatland complex, southern Finland

Paul J.H. Mathijssen [a, *], Minna Väliranta [a], Aino Korrensalo [b], Pavel Alekseychik [c], Timo Vesala [c, d], Janne Rinne [e], Eeva-Stiina Tuittila [b]

[a] Department of Environmental Sciences, University of Helsinki, Finland
[b] School of Forest Sciences, Joensuu Campus, University of Eastern, Finland
[c] Department of Physics, University of Helsinki, Finland
[d] Department of Forest Sciences, University of Helsinki, Finland
[e] Department of Geosciences and Geography, University of Helsinki, Finland

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ABSTRACT

Holocene peatland development and associated carbon (C) dynamics were reconstructed for a southern boreal Finnish peatland complex with fen and bog areas. In order to assess the role of local factors and long-term allogenic climate forcing in peatland development patterns, we studied a total of 18 peat cores and reconstructed vertical peat growth and lateral peat area expansion rates, the C accumulation rate (CAR), past vegetation composition and past methane ($CH_4$) fluxes. We combined fossil plant data with measured contemporary $CH_4$ flux – vegetation relationship data to reconstruct $CH_4$ fluxes over time. When these reconstructions were added to the CAR estimations, a more complete picture of Holocene-scale C dynamics was achieved. Basal peat ages showed that expansion of the peat area was rapid between 11,000 and 8000 cal. BP, but decreased during the dry mid-Holocene and is probably currently limited by basal topography. A similar pattern was observed for peat growth and CAR in the fen core, whereas in the bog core CAR increased after ombrotrophication, i.e. after 4400 cal. BP. The effect of fire on vegetation and CAR was more conspicuous at the bog site than at the fen site. The $CH_4$ flux reconstructions showed that during the Holocene $CH_4$ emissions at the fen site decreased from 19 ± 15 to 16 ± 8 g $CH_4$ $m^{-2}$ $yr^{-1}$ and at the bog site from 20 ± 15 to 14 ± 8 g $CH_4$ $m^{-2}$ $yr^{-1}$. Our results suggest that a combination of changing climate, fire events and local conditions have modified the autogenic peatland development and C dynamics.



## 1. Introduction

Climate forcing of peatlands is dualistic: peatlands are an effective sink of atmospheric carbon dioxide ($CO_2$) but are also an important source of methane ($CH_4$) (Frolking et al., 2006; Frolking and Roulet, 2007; Korhola et al., 2010; Yu, 2011; Petrescu et al., 2015). During the Holocene (the last ca. 11,700 years), high latitude peatlands have accumulated approximately 500 Pg carbon (C) (Pg = $10^{15}$ g), which is equivalent to approximately 30% of global soil organic C (Yu, 2012), and nearly equal to the pre-industrial atmospheric C reservoir. $CH_4$ fluxes account for a significant proportion, up to 25% of the net ecosystem C balance of peatlands (Limpens et al., 2008). However, the magnitude of the $CO_2$ sink and $CH_4$ source forcing has varied throughout the Holocene (Yu, 2011). Moreover, peatlands grow in vertical and horizontal directions (Korhola, 1994), while accumulation rates or development pathways are not constant through time (Mäkilä, 1997). Peatland C dynamics are regulated to a great extent by climatic factors (Gorham, 1991; Dorrepaal et al., 2009; Fan et al., 2013), which have varied over time and are predicted to rapidly change in the future (Gong et al., 2013). Hence, in order to profoundly understand future peatland C dynamics, we need to understand the developmental history of this large C reservoir in response to past variations in climate.

In addition to climatic factors, such as temperature and moisture conditions, peatland $CO_2$ and $CH_4$ fluxes are closely linked to vegetation composition, in particular through differences between plant species in their productivity and litter decomposability

* Corresponding author.
*E-mail address:* paul.mathijssen@helsinki.fi (P.J.H. Mathijssen).

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(Moore and Knowles, 1989; Moore et al., 1990; Yavitt et al., 1997; Leppälä et al., 2008, 2011b; Laine et al., 2012). In addition, vegetation can control $CH_4$ transportation from the soil to the atmosphere and can offer microhabitats for the microbial communities responsible for $CH_4$ oxidation (Bellisario et al., 1999; Larmola et al., 2010).

The autogenic ombrotrophication process, the so called fen-bog transition, produces changes in vegetation structure and water table depth (Hughes, 2000; Tuittila et al., 2013). Young peatlands are predominantly characterized by sedge-dominated fen vegetation and high $CH_4$ emissions (Leppälä et al., 2011a). In fens, the decomposition rate is generally rapid, and therefore C accumulation is slower when compared to *Sphagnum* dominated bogs (Tolonen and Turunen, 1996; Drewer et al., 2010). Accelerated vertical peat growth during the fen-bog transition, associated with an increase in the proportion of *Sphagnum* and the depth of the water table, results in more effective C uptake and decreased $CH_4$ emissions. Lateral peatland growth increases the surface area of effective C uptake but may also increase $CH_4$ emissions (Korhola et al., 1996).

As a consequence of the strong relationship between vegetation and $CH_4$ fluxes, vegetation composition can be used as a proxy for current $CH_4$ fluxes (Bubier et al., 1995; Dias et al., 2010; Couwenberg et al., 2011; Audet et al., 2013; Gray et al., 2013), and also for past $CH_4$ fluxes if the fossil plant assemblages are known. The contemporary vegetation-$CH_4$ flux relationship has been intensively explored to predict $CH_4$ fluxes by applying site type (Couwenberg et al., 2011), moss species (Bubier et al., 1995), vascular plant species (Audet et al., 2013) or both (Dias et al., 2010; Gray et al., 2013), as well as plant functional traits (Gray et al., 2013).

There is still a large amount of uncertainty in regard to how C dynamics in peatlands will be affected by changing climatic conditions (Frolking et al., 2011). For a comprehensive understanding of long-term C accumulation dynamics and associated climate forcing, vertical peat accumulation rates and lateral expansion have to be taken into account. To reach this, multiple cores within one peatland should be used to reconstruct peatland development and C accumulation history, accompanied by multiple dated basal peat samples to capture the lateral expansion of the peat area. However, relatively few studies to date have incorporated lateral expansion into Holocene-scale peatland dynamics reconstructions (Korhola, 1994; Mäkilä, 1997; Bauer et al., 2003; Mäkilä and Moisanen, 2007), and even fewer studies have applied a three-dimensional approach for modelling of C dynamics (Korhola et al., 1995, 1996; Mathijssen et al., 2014).

To increase the understanding of climate-peatland interactions, we undertook a comprehensive reconstruction of C dynamics in a large boreal peatland complex that has bog and fen parts. This included a reconstruction of $CH_4$ fluxes based on past vegetation composition. A reconstruction of $CH_4$ fluxes back through time has been performed before (e.g. Steinmann et al., 2006; Mathijssen et al., 2014), but not using the quantitative methods applied in this study. As $CH_4$ dynamics differ between peatland successional stages (Leppälä et al., 2011b), reconstruction of $CH_4$ fluxes over the developmental history of a peatland should not solely rely on $CH_4$ flux-relationships derived from mature peatland ecosystems. Therefore, we quantified the $CH_4$ flux and vegetation composition relationship from two different boreal Finnish peatland areas; one representing young peatland stages and the other representing older peatland stages.

## 2. Material and methods

We studied horizontal peatland expansion and vertical peat accumulation patterns in a southern boreal peatland at Siikaneva, southern Finland using multiple basal peat ages and two peat cores with multiple dates. To calculate Holocene C accumulation rates, the chronological data were combined with bulk density (BD) and loss on ignition (LOI) data. Loss on ignition is the relative decrease in peat mass after combustion for 2 h at 550 °C and is used as a measure for organic matter content. To estimate $CH_4$ flux rates through time we first established a relationship between current vegetation composition and measured $CH_4$ fluxes. We then used fossil plant assemblages to reconstruct past $CH_4$ fluxes. In order to take into account differing $CH_4$ fluxes between young and old developmental stages, we incorporated $CH_4$ flux data measured from a peatland succession series located at a land uplift coast in Central Western Finland to represent the young peatland developmental stages. $CH_4$ flux data measured from Siikaneva represented the older developmental stage.

### 2.1. Study site

The studied peatland complex, Siikaneva, is located in southern Finland, 61°50′N, 24°12′E, 160 m a.s.l. (Fig. 1a). Siikaneva is an open peatland that has bog and fen areas. Large oligotrophic fens form the majority of the total area of c. 12 $km^2$. Peat depth ranges from 2 to 6 m. Several previous studies have explored contemporary vegetation and C dynamics at Siikaneva (Aurela et al., 2007; Riutta et al., 2007; Rinne et al., 2007; Laine et al., 2012). In brief, most of the fen surface has a relatively uniform lawn topography, with the vegetation consisting of a moss layer (*Sphagnum balticum* (Russow) C.E.O. Jensen, *Sphagnum majus* (Russow) C.E.O. Jensen and *Sphagnum papillosum* Lindb.) and a sparse vascular plant layer dominated by Cyperaceae (*Eriophorum vaginatum* L., *Carex rostrata* Stokes and *Carex limosa* L.). The bog areas (Fig. 1c) have a distinctive microtopographical pattern with hummocks, dominated by *Sphagnum fuscum* (Schimp.) H. Klinggr. and *Sphagnum rubellum* Wilson, lawns with mostly *Sphagnum magellanicum* Brid. and *S. rubellum*, wet hollows dominated by *Sphagnum cuspidatum* Ehrh. Ex Hoffm. and *S. majus*, and ponds and bare peat surfaces without any *Sphagnum* vegetation. Dwarf shrubs, such as *Andromeda polifolia* L., *Calluna vulgaris* (L.) Hull and *Empetrum nigrum* L., are present on the hummocks. *E. vaginatum* grows on the dry lawns and encroaches onto the hummocks. *Rhynchospora alba* L., *Carex limosa* L. and *Scheuchzeria palustris* L. occur in wet hollows and border bare peat surfaces.

### 2.2. Sampling

To study vertical and horizontal peat growth, a total of 18 peat cores were taken with a 5-cm-diameter Russian peat corer (Fig. 1b). 16 cores taken in 2010 were used to study lateral expansion and C accumulation. In some cases, the topmost 50–100 cm had to be excluded from the peat cores because the peat was too wet and loose to be sampled. Two cores (SiiB and SiiF) taken in 2012 were used to study vertical peat development. Core SiiB was taken from the bog area and core SiiF from the oligotrophic fen area, both located in the eastern part of the peatland (Fig. 1b). All samples were taken from intermediate lawn surfaces, because the species assemblages of these habitats are most sensitive to changing hydrological conditions (De Vleeschouwer et al., 2010). Coring point SiiB was dominated by *S. rubellum*, with *S. fuscum* and *S. balticum* present, and core SiiF was dominated by *S. papillosum*.

### 2.3. Dating and age-depth modelling

In this study, a total of 30 samples were dated with accelerator mass spectrometry radiocarbon dating at the Finnish Museum of Natural History (LUOMUS) and Poznan Radiocarbon Laboratory.