Monitoring the Multi-Year Carbon Balance of a Subarctic Palsa Mire with Micrometeorological Techniques

Torben R. Christensen, Marcin Jackowicz-Korczyński,
Mika Aurela, Patrick Crill, Michal Heliasz,
Mikhail Mastepanov, Thomas Friborg

Abstract This article reports a dataset on 8 years of monitoring carbon fluxes in a subarctic palsa mire based on micrometeorological eddy covariance measurements. The mire is a complex with wet minerotrophic areas and elevated dry palsa as well as intermediate sub-ecosystems. The measurements document primarily the emission originating from the wet parts of the mire dominated by a rather homogenous cover of *Eriophorum angustifolium*. The CO₂/CH₄ flux measurements performed during the years 2001–2008 showed that the areas represented in the measurements were a relatively stable sink of carbon with an average annual rate of uptake amounting to on average $-46 \text{ g C m}^{-2} \text{ y}^{-1}$ including an equally stable loss through CH₄ emissions ($18\text{--}22 \text{ g CH}_4\text{-C m}^{-2} \text{ y}^{-1}$). This consistent carbon sink combined with substantial CH₄ emissions is most likely what is to be expected as the permafrost under palsa mires degrades in response to climate warming.

Keywords Carbon cycling · Subarctic mire · Permafrost · Land–atmosphere exchange · Climate change

INTRODUCTION

Palsa mires are complex wetland ecosystems with permanently frozen peat components. They are characteristic and unique features of high latitude environments in parts of Fennoscandia, Russia, Canada and Alaska. In recent decades, palsas have been degrading throughout their distribution range in the northern hemisphere (Luoto et al. 2004a, b). These marginal permafrost features appear to be highly sensitive to climatic conditions, and the recent decline of palsas in Europe has been linked to regional climatic warming (Sollid and Sørbel 1998). Consequently,

the climate changes projected for future decades may cause a further extensive degradation of permafrost in mires.

Palsa mires in Fennoscandia occur in areas with a mean annual air temperature near 0 °C. Ecosystems along the 0 °C mean annual isotherm are arguably among the most sensitive to changing climate, and mires in the subarctic regions have significant exchanges of the important greenhouse gases methane (CH₄) and carbon dioxide (CO₂) with the atmosphere. These exchanges are intimately related to temperature and hydrology, and alterations in permafrost coverage, which affect both of those, could have dramatic impacts on the combined climate forcing from these exchanges. Recent studies have shown that palsa mire ecosystems in Sweden are subject to dramatic changes in the distribution of permafrost and vegetation (Christensen et al. 2004; Malmer et al. 2005; Johansson et al. 2006) and also that this is a general phenomenon at least for most of northern Scandinavia (Bosiö et al. 2012). These changes are most likely caused by a warming that has been observed during recent decades.

In northern Sweden, we have previously documented dramatic ecosystem changes as a consequence of the ongoing permafrost thaw (Christensen et al. 2004; Johansson et al. 2006). A substantial change in the surface hydrology follows the palsa degradation and subsequent increases in CH₄ emissions (Christensen et al. 2004) but also in the CO₂ sink strength at the landscape scale has been documented (Johansson et al. 2006). Annual total C budgets have been documented for individual palsa ecosystem components based on automatic chamber measurements (Bäckstrand et al. 2010) and recently the annual dissolved organic carbon (DOC) export terms have been documented from the same parts of the palsa complex (Olefeldt et al. 2012). Also the lakes in the area have been subjects to recent studies both in the terms of general

organic carbon supply (Karlsson et al. 2010) and in terms of their methane dynamics (Wik et al. 2012). Initial attempts to synthesize the mass balance of the entire Torneträsk catchment have also been conducted (Christensen et al. 2007) pointing at the needs for better data coverage. We have, however, not previously documented the details of the interannual variability in the combined atmospheric carbon fluxes based on the long-term micro-meteorological monitoring efforts.

Hence, this study presents a multi-year dataset on CO₂ fluxes from a subarctic palsa mire site and associated CH₄ fluxes (Jackowicz-Korczyński et al. 2010) to arrive at an evaluation of the interannual variability of atmospheric C fluxes in this environment.

MATERIALS AND METHODS

Site Description

The study site, Stordalen Mire, is a palsa mire located in subarctic Sweden (68°20'N, 87°19'03'E, alt. 363 m a.s.l.). The mire complex has two major topographical features, elevated dry ombrotrophic parts underlain by permafrost mixed with wet minerotrophic depressions largely permanently saturated by water. Each of these sub-ecosystems has slightly alternating plant species composition but in general the wet areas are dominated by tall graminoids (mainly *Eriophorum angustifolium*) whereas the dry parts mostly have mosses, lichens and dwarf shrubs (Malmer et al. 2005). Apart from these two major topographical features, small open water pool formations, streams and at the margins also single stands of mountain birch *Betula pubescens* are present in the mire complex. The peat depth is up to 3 m on the palsa plateau and the late summer active layer thickness is ca. 60 cm (Malmer et al. 2005; Johansson et al. 2006). Within the mire topography also thermokarst erosion processes are active and a currently progressing increase in active layer thickness leading ultimately to palsa collapses and disappearance of the permafrost in the wet areas has been documented for Stordalen specifically (Johansson et al. 2006) and for the Torneträsk area in general (Åkerman and Johansson 2008). The eastern part of the mire is bordered by the shallow Lake Villasjön (0.17 km², max depth 1.3 m). Figure 1 presents an aerial photograph of the southern-east part of the Stordalen mire complex showing the major topographical features as well as the placement of the eddy covariance (EC) tower setup. Malmer et al. (2005) provides a more detailed description of the spatial distribution of the Stordalen mire vegetation and how this has changed in recent decades.

The mire is receiving relatively small amounts of precipitation. The average annual precipitation for the years

2004–2008 was 340 mm y⁻¹ and the average annual temperature was −0.3 °C. During the studied period 2001 was the coldest (−1.2 °C) out of the 8 years and also the one with shortest growing season (see below and Table 1). Except for 2008, which was relatively cold, the temperature record from the mire shows an increasing trend over the study period resembling the accelerating increase in temperature since the late 1980s reported from the 100-year record at nearby Abisko Scientific Research Station (Callaghan et al. 2010).

The results obtained with the use of the EC method represent the average functioning of land–atmosphere interactions within the footprint area. The size of this footprint is mainly dependent on a combination of atmospheric stability, surface roughness, as well as the measurement height. We analyzed the footprint according to the model presented by Schuepp et al. (1990) and used a distance within which 80 % of the measured flux value originates. This distance in our EC setup for the daytime conditions ranged ~300 m and for nighttime up to 400–500 m. The mire has a very stable and well-defined easterly–westerly wind direction distribution (95 % of winds are evenly distributed along the Lake Torneträsk Valley) and very rarely winds from north and south. The fluxes were weighed according to the wind direction frequency distribution calculated for every 10° sector and most of this analysis represents a comparison of east versus west (Jackowicz-Korczyński et al. 2010). Figure 2 shows the wind rose and the predominant wet parts of the mire seen by the tower. On average the footprint of the tower is about 83 % wet areas dominated by tall graminoid vegetation, roughly 11 % is the hummock/palsa vegetation type and the rest of the categories are negligible in the time series as a whole. However, the latter may at certain times and conditions still show an influence on the fluxes.

Measurements

The measurements are based on the EC method (Aubinet et al. 2000; Baldocchi 2003). The instrumentation core consist of a 3-m high mast equipped with an R3-50 three axis anemometer (Gill Instruments Ltd., Lymington, Hampshire, UK) combined with an open-path CO₂/H₂O gas analyzer LI-7500 (Li-Cor, Inc., Lincoln, NE, USA) and Tunable Diode Laser trace gas detector (TDL) (Aerodyne Res., Inc., Billerica, MA, USA) for measuring CH₄ fluxes. Together with the flux measurements a set of basic meteorological variables were acquired with the use of a CR10x data logger (Campbell Scientific, Inc., Logan, UT, USA). In addition, an automatic digital camera system operating in the visible part of the spectrum (Axis 200+, Axis Communications AB, SE) was used for studying snow cover dynamics as well as basic plant phenology

Fig. 1 Aerial photograph of Stordalen mire showing the south-eastern part of the mire complex with the EC tower setup in the centre of the picture frame. The small cottage and the Lake Villasjön are

visible in the upper part of the photograph. Picture taken along the major W–E wind flow (see Fig. 2) during a helicopter survey over the studied area in August 2008 (photo by M. Heliasz)

(e.g. leaves on birches, flowering of *Eriophorum*). The meteorological conditions were obtained with a time resolution of 1 h while the CO₂ and CH₄ fluxes were calculated on a half-hourly basis. Detailed description of the instrumentation setup is presented in the study of Jackowicz-Korczyński et al. (2010). All flux calculations were performed off line with 2D coordinate rotation applied. The CO₂ fluxes were post processed with use of Alteddy software (Mauder et al. 2008) and the CH₄ fluxes were calculated according to Friborg et al. (1997, 2000). Flux data were acquired by EdiSol program (Moncrieff et al. 1997) and averaged by half-hourly periods. For both the CO₂ and the CH₄ signals the running mean of 200 s time constant was used for detrending and the 2D coordinate rotation was

applied for correcting the EC tower misalignment. The CO₂ flux measurements were performed continuously during all years while the CH₄ flux measurements were launched in early May and maintained until the end of the year for two consecutive years 2006 and 2007. In order to fill the gap in the deep winter time measurements of the CH₄ fluxes, a 2-week measurement campaign was carried out in 2008 to analyze the wintertime CH₄ emission levels. Only three (2006–2008) out of the 8 years have enough reliable data from the winter season for a fully measurement-based annual C budget to be obtained (Fig. 3). We have, however, also made a rough estimation for the remaining years based on the average winter flux in the years with reliable data (Table 1).

Table 1 The growing season CO₂ and CH₄ balances measured by EC tower compiled with major phenological and climatic parameters recorded at Stordalen in 2001–2008

Year	Cumulative carbon balance (g C m ⁻² y ⁻¹)			Air temp. (°C)			Snow melt (DOY)	Growing season (DOY)		
	CO ₂	CH ₄	C	Min.	Avg.	Max.		Start	Stop	Duration
2001	–87 (–20) ^a		–74 (0)	–33.3	–1.17	23.6	121	144	243	99
2002	–107 (–40) ^a		–94 (–20)	–33.0	–0.68	24.3	116	138	243	105
2003	–109 (–42) ^a		–96 (–22)	–39.1	–0.52	24.8	110	125	234	109
2004	–160 (–93) ^a		–147 (–73)	–34.1	–0.33	24.6	111	117	231	114
2005	–127 (–60) ^a		–114 (–40)	–34.6	–0.16	25.4	120	147	258	111
2006	–147 (–84)	11 (18)	–136 (–66)	–38.8	–0.22	23.2	121	113	239	126
2007	–166 (–95)	15 (22)	–151 (–73)	–34.1	–0.19	27.5	119	142	252	110
2008	–159 (–91)		–146 (–71)	–30.5	–0.67	22.5	124	144	260	116
Average	–133 (–66)	13 (20)	–120 (–46)	–34.7	–0.49	24.5	118	134	245	111

The admittedly rough estimates of the full annual C balance in brackets are also presented based on an average of the measured winters. Methane flux numbers are from Jackowicz-Korczyński et al. (2010). The total C numbers are estimated on the average of 2 years (2006–2007) of available CH₄ EC flux data

^a Value represented by average winter flux calculated from 2006 to 2008 for CO₂ and 2006 to 2007 for CH₄

Gap Filling

After post processing the raw half-hourly flux data were screened and the periods with EC system malfunctions and maintenance has been removed. To reduce the influence of the open-path sensor heating effects (Burba et al. 2008), a significant CO₂ uptake signal recorded during the cold off-season periods were also discarded from further analysis. In addition, all half-hourly CO₂/H₂O flux data recorded during rain events were rejected to avoid uncertainties occurring in open-path systems through rainy conditions. Moreover, to eliminate the influence of the stable lower boundary conditions all flux data recorded with $u^* < 0.1 \text{ m s}^{-1}$ were discarded. Finally, in analysing fluxes the quality flag classification system proposed by Foken et al. (2004) was applied. The CH₄ fluxes were gap filled based on the exponential soil temperature relationship presented by Jackowicz-Korczyński et al. (2010) while with the CO₂ flux signal two different approaches were applied. The daytime CO₂ fluxes recorded during the growing season were gap filled by applying the light response equation (1) while the rest of the fluxes were parameterized with the night respiration equation (2) (Falge et al. 2001).

$$\text{NEE}_{\text{day}} = -(F_{\text{csat}} + R_d)(1 - \exp(-\alpha Q / (F_{\text{csat}} + R_d))) + R_d, \quad (1)$$

$$\text{NEE}_{\text{night}} = R_0 \exp(\tau T_a), \quad (2)$$

where NEE_{day} is measured CO₂ flux during the day time conditions ($Q > 10 \mu\text{mol m}^{-2} \text{ s}^{-1}$) in $\text{mg m}^{-2} \text{ s}^{-1}$, $\text{NEE}_{\text{night}}$ is measured CO₂ flux during the night time conditions ($Q \leq 10 \mu\text{mol m}^{-2} \text{ s}^{-1}$) in $\text{mg m}^{-2} \text{ s}^{-1}$, F_{csat} is the

saturation value of the light respond curve in $\text{mg m}^{-2} \text{ s}^{-1}$, R_d is the intercept of the light respond curve (the respiration rate at dawn and dusk) in $\text{mg m}^{-2} \text{ s}^{-1}$, α is the initial slope of the light respond curve in $\text{mg } \mu\text{mol}^{-1}$, Q is the photosynthetic photon flux density in $\mu\text{mol m}^{-2} \text{ s}^{-1}$, R_0 is the base respiration in $\text{mg m}^{-2} \text{ s}^{-1}$, T is the coefficient of the temperature response curve in $^{\circ}\text{C}^{-1}$, T_a is the air temperature in $^{\circ}\text{C}$.

The growing season was defined as starting a week before the point in time at which the daily average air temperature exceeded $+5^{\circ}\text{C}$ for more than three consecutive days. It lasted until air temperatures dropped down below this same limit in the fall. The day/night time separation was based on a threshold of photosynthetic photon flux density Q (night $\leq 10 \mu\text{mol m}^{-2} \text{ s}^{-1} < \text{day}$). Table 1 presents the compilation of the basic phenological and climatological parameters as well as the accumulated fluxes of CO₂ and CH₄. The estimation of the light response curve factors in Eq. (1) was performed for successive weekly periods beginning from the week preceding the start of the growing season until the week after the growing season is over. Estimation of Eq. (2) coefficients was based on weekly average values of measured NEE and air temperature during the whole year. In estimating all the above-mentioned coefficients only the measurements classified with the flag values 1–3 in Foken et al. (2004) data quality flag system (from 1 high quality to 9 low quality) were used. Figure 4 presents the result of the multi-year light response curve parameters as well as the night time respiration function (2) for Stordalen mire. The Stordalen results are here compared with an example of another subarctic fen—Kaamanen mire located in northern Finland ($68^{\circ}08'\text{N}$, $27^{\circ}17'\text{E}$, 155 m a.s.l.)

Fig. 2 Schematic map of Stordalen mire complex with the location of the EC tower and the frequency wind direction distribution recorded during 2001–2008

(Aurela 2005). The Kaamanen site is as Stordalen a mire complex but characterised primarily by *Ericales-Pleurozium* string tops, *Betula-Sphagnum* string margins, *Trichophorum* tussock flarks, and *Carex-Scorpidium* wet flarks (Maanaviila et al. 2011). As the two sites are

relative close and at the same latitude this comparison is made to study the local–regional effects of climate differing depending on gradients such as from a coastal mountain precipitation shadow to a more continental setting.

Fig. 3 Cumulative graphs of **a** air temperature, **b** photosynthetic active radiation (PAR) and **c** net ecosystem exchange during the 8 years of monitoring based on half-hourly averaged values. *Dashed lines* The start and end of the growing seasons as defined in this study. The growing season start for the years without winter data is set at the average of the three measured years. The numbers in **c** refer to the growing season accumulated carbon uptake and the numbers in *parentheses* the full annual sum for the years with reliable winter data (Table 1)

Fig. 4 Comparison of the seasonal variations of the light response function parameters (Eq. 1) and the night time respiration rates for consecutive 1-week period between the Stordalen and Kaamanen site. *Error bars* The 95 % confidence intervals

RESULTS AND DISCUSSION

During the years where a full measurement-based annual atmospheric CO₂ balance was made based on the EC system the mire acted as a carbon sink ranging between -84 and -95 g CO₂-C m⁻² y⁻¹. When including the years for which the winter fluxes were estimated based on the average measured flux-years the annual balance average -46 g CO₂-C m⁻² y⁻¹ (Table 1). The CH₄ emissions totaled 18 – 22 g CH₄-C m⁻² y⁻¹ (Jackowicz-Korczyński et al. 2010) corresponding to a substantial loss in terms of carbon of on average one-third of the CO₂ uptake. This amounts to an average atmospheric carbon balance for the fetch area ranging between near neutral to an uptake of -73 g C m⁻² y⁻¹ (Table 1). For a full balance to be obtained both the DOC export and the emissions of volatile organic compounds (VOC) must be considered. According to recent data, the DOC export term amounts to 7 – 8 g C m⁻² y⁻¹ from the part of the mire covered by the EC tower (Olefeldt and Roulet 2012) and the VOC fluxes amounts to only a fraction of this (Bäckstrand et al. 2008; Holst et al. 2010; Olefeldt et al. 2012). This leaves this wet part of the mire complex as a substantial and consistent C sink with only the first year (2001) of measuring being near to neutral or possibly a small source. That particular year was also characterised by seeing the shortest growing season (Table 1). The largest variations between years in the observed fluxes appeared in general when the vegetation is switching on/off the photosynthesis (June and September) while the mid-summer maximal uptake rates are quite stable over time. Similar observations were derived from the CO₂ flux interannual studies presented by Aurela et al. (2004) for the Kaamanen site. This could be explained by the solar energy availability related to the similar latitude position of both the subarctic sites. While the date of snow melt varied between the years with <2 weeks, the defined start of the growing season varied by more than a month (Fig. 3; Table 1). Possibly as a consequence, a relationship between date of snow melt and accumulated growing season carbon flux could not be as clearly established as otherwise documented for other high northern ecosystems (Aurela et al. 2004; Grøndahl et al. 2008; Lund et al. 2012). Other sites in the circumpolar North has also failed to show this clear relationship between date of snow melt and growing season uptake (Humphreys and Lafleur 2011; Parmentier et al. 2011). In our particular case, this may be due to the relatively similar climate conditions in the years of measurement but also because our measurements represent the vegetation signal originating from permafrost free water saturated surfaces dominated by a dense cover of *Eriophorum angustifolium*. The tall graminoid vegetation in our case is less sensitive to the hydrological conditions which are influencing the

Kaamanen annual budgets and makes these very dependent on the date of the snow melt (change of 2 g C m⁻² y⁻¹ in annual CO₂ balance per 1 day change in the snow melt day according to Aurela et al. (2004)). The Stordalen mire surface hydrology is complex due to the presence of permafrost but within the EC fetch this situation is relatively stable with a continuous supply of water (and nutrients) for the dominating plant communities. The difference is, hence, between a gradually through the season drained site (Kaamanen) and one that has complex variations but a constant high water level in the main fetch of the EC tower (Stordalen). This may explain the strong and stable sink function presented in the Stordalen EC flux data. Finally, by comparing the NEE observed at both the sites the Stordalen data shows higher respiration rates than Kaamanen. This could be explained by the leaf area index differences between the sites. This vegetation-dependent parameter for the dominant cover in Stordalen EC tower fetch range >2 (T. Holst, personal communication), substantially higher than the 0.7 reported for Kaamanen (Aurela et al. 2004). The dense cover of *Eriophorum angustifolium* at Stordalen results in both the higher photosynthesis and the higher respiration.

While a relationship between strictly the date of snow-melt and the growing season uptake could not be established the growing season length did seem to relate to accumulated NEE (Fig. 5). The year with the earliest onset of net carbon accumulation, 2004, also shifted earlier and more sharply to a carbon source towards the end of the season resulting in the biggest autumn C loss of all years and as a result the lowest annual carbon uptake. This loss is not easily explained by climatic parameters but could be due to the effects of a massive insect outbreak by the autumnal moth *Epirrita autumnata* that in the peak of the

Fig. 5 The growing season accumulated NEE against the length of the growing season as defined in this study. The line is marginally statistically significant ($P = 0.05$)

2004 growing season almost completely defoliated the mountain birches in the area (Heliasz et al. 2011) and also some of the deciduous dwarf shrub communities on the mire. This could have led to both the reduced photosynthesis to the extent where the tower footprint covers the defoliated birch forest and the increased respiration (Heliasz et al. 2011).

The evolution of the light response curve parameters during the season shows faster vegetation response to the light compared with published data from a Finnish subarctic fen (Aurela et al. 2004). Although these are comparable ecosystems at roughly the same latitude this comparison shows clearly the effect of the Stordalen site having a milder climate influenced by the warm North Atlantic Current while the Kaamanen site is subject to a more continental and prolonged colder winter conditions which results in the delayed growing season onset at Kaamanen compared with Stordalen (Fig. 4).

A detailed fetch analysis of the CH₄ measurements showed indications of an influence from Lake Villasjön in the eastern sector (Jackowicz-Korczyński et al. 2010). Larger CH₄ emission was observed from the lake sector. This is particularly seen at higher air temperatures and could be explained by a bubble release of CH₄ increasingly triggered as the temperature of the lake rises. In terms of the CO₂ fluxes the influence of the lake is probably less pronounced. However, the lake is during the growing season a continuous source of CO₂ (Karlsson et al. 2010) increasing the respiration term during the night time and possibly lowering the total uptake during the day. The lake influence on the CO₂ fluxes, although marginal, may only have lowered the estimates for the potential CO₂ uptake by the terrestrial parts of the mire complex. But many questions remain to be studied on lake and stream influences on the ecosystem atmosphere exchanges in the area as a whole.

The consistent and minor between year variation in the seasonal distribution of carbon fluxes in the Stordalen mire is illustrated by Fig. 3c. This limited variation is probably driven by the fetch bias towards the wet minerotrophic parts of the mire. Despite all uncertainties with possible influences of lake fluxes the wet areas will have less variable fluxes due to constant saturated floating mat conditions. Figure 6 summarises the averaged month-by-month differences in accumulated NEE illustrating that although the system is a consistent sink it is as all northern ecosystems dependent on a relatively short period of only 3 months per year of actual carbon uptake.

The strong influence on the overall carbon fluxes of the high CH₄ emissions confirms the findings by Johansson et al. (2006) showing that as the permafrost thaws and the wet conditions that the current study largely have covered increases in its relative distribution the palsa mire makes a

Fig. 6 The monthly average balances of NEE recorded during selected years 2004–2008. *Error bars* The variations of the monthly average NEE observed within the 5 years used

shift towards being a much stronger agent of greenhouse warming. This emphasises the importance of documenting multiple greenhouse gas species when analysing ecosystem functioning for the analysis of land–atmosphere interactions in a climate perspective.

It is nevertheless, interesting to compare the interannual variability in the functioning of the wet part of the palsa mire complex documented here with that of the surrounding ecosystems. While we see a relative consistency in the C sink functioning in this study, we observe larger inter-annual fluctuations in the closest by elevated palsa part of the mire (Bäckstrand et al. 2010; Olefeldt et al. 2012) as also seen in other northern peatlands (e.g. Roulet et al. 2007). This contrast is particularly striking when compared to the highly sensitive surrounding birch forest (Heliasz et al. 2011; unpublished results). The latter has a variability that varies according to comparable measurements during the same time period as that of this study from an annual source of 31 g CO₂–C m⁻² y⁻¹ to an uptake of –21 g CO₂–C m⁻² y⁻¹ (Heliasz et al., unpublished results). This clearly shows the complexity of this subarctic landscape in relation to land–atmosphere exchanges and it points at the importance of long-term monitoring efforts to obtain a comprehensive understanding of this variability and the ecosystem sensitivity to changes at the landscape scale.

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AUTHOR BIOGRAPHIES

Torben R. Christensen (✉) is a Professor at the Department of Physical Geography & Ecosystem Science, Lund University specializing in northern ecosystem biogeochemistry with emphasis on trace gas exchanges. He is also currently co-leading Greenland Climate Research Center at the Greenland Institute of Natural Resources. *Address:* Department of Physical Geography and Ecosystem Science, Lund University, Sölvegatan 12, 223 62 Lund, Sweden. e-mail: torben.christensen@nateko.lu.se

Marcin Jackowicz-Korczyński is a Researcher Engineer at the Department of Physical Geography & Ecosystem Science, Lund University. He specializes in application and development variety of micro- and macroscale instrumental methods for studying ecosystem processes.

Address: Department of Physical Geography and Ecosystem Science, Lund University, Sölvegatan 12, 223 62 Lund, Sweden. e-mail: marcin.jackowicz-korczynski@nateko.lu.se

Mika Aurela is a Senior Researcher at the Finnish Meteorological Institute. He specializes in the micrometeorological flux measurements of the greenhouse gases in different northern ecosystems.

Address: Climate Change Research, Finnish Meteorological Institute, Erik Palménin aukio 1, 00560 Helsinki, Finland. e-mail: mika.aurela@fmi.fi

Patrick Crill is a Professor of Biogeochemistry at the Department of Geological Sciences of Stockholm University. He specializes in trace gas biogeochemistry and the study of biosphere atmosphere exchange.

Address: Department of Geological Sciences, Stockholm University, Svante Arrhenius väg 8C, 106 91 Stockholm, Sweden. e-mail: patrick.crill@geo.su.se

Michał Heliasz is a PhD student at the Department of Physical Geography and Ecosystem Science, Lund University, Sweden. He specializes in the mountain birch forest carbon flux dynamics.

Address: Department of Physical Geography and Ecosystem Science, Lund University, Sölvegatan 12, 223 62 Lund, Sweden. e-mail: Michal.Heliasz@nateko.lu.se

Mikhail Mastepanov is a Researcher at the Department of Physical Geography & Ecosystem Science, Lund University. He specializes in automatic measurement systems for field and lab applications.

Address: Department of Physical Geography and Ecosystem Science, Lund University, Sölvegatan 12, 223 62 Lund, Sweden. e-mail: Mikhail.Mastepanov@nateko.lu.se

Thomas Friborg is an associate professor at Department of Geography and Geology and member of the CenPerm research center. He specializes in micrometeorological measurements of greenhouse gasses and climatic feedbacks in the Arctic.

Address: Department of Geography and Geology, University of Copenhagen, Øster Voldgade 10, 1350 Copenhagen K, Denmark. e-mail: tfj@geo.ku.dk