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Annual carbon gas budget for a subarctic peatland, northern Sweden

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Abstract

Temperatures in the Arctic regions are rising, thawing permafrost and exposing previously stabile soil organic carbon (OC) to decomposition. This can result in that northern latitude soils which have accumulated large amounts of OC potentially shift from atmospheric C sinks to C sources with positive feedback on climate warming. In this paper, we estimate the annual net C gas balance (NCB) of the subarctic mire Stordalen, based on automatic chamber measurements of CO_2 and total hydrocarbon (THC; CH_4 and NMVOCs) exchange. We studied the dominant vegetation communities with different moisture and permafrost characteristics; a dry Palsa underlain by permafrost, an intermediate thaw site with *Sphagnum* spp. and a wet site with *Eriophorum* spp. where the soil thaws completely. Whole year accumulated fluxes of CO_2 were estimated to 30, −35 and −35 g C m^{-2}, respectively for the Palsa, *Sphagnum* and *Eriophorum* sites (positive flux indicates an addition of C to the atmospheric pool). The corresponding annual THC emissions were 0.52, 6.2 and 32 g C m^{-2} for the same sites. Therefore, the NCB for each of the sites were 30, −29 and −3.1 g C m^{-2}, respectively for the Palsa, *Sphagnum* and *Eriophorum* site. On average, the whole mire was a sink of CO_2 (−2.6 g C m^{-2}) and a source of THC (6.4 g C m^{-2}) over a year. Consequently, the mire was a net source of C to the atmosphere (3.9 g C m^{-2}). Snow season efflux of CO_2 and THC emphasize the importance of winter measurements for complete annual C budgets. Decadal vegetation changes at Stordalen indicate that both the productivity and the THC emissions increased between 1970 and 2000. Considering the GWP_{100} of CH_4, the net radiative forcing on climate increased 21% over the same time. Conclusively, reduced C compounds in these environments have high importance for both the annual C balance and climate.

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1 Introduction

Northern latitude soils store a large amount of organic carbon (C) due to a climate that causes low decomposition rates relative to production rates. The amount of organic C that is stored in northern latitude permafrost soils has been estimated to be as high as 1400 to 1850 Gt (McGuire et al., 2008), which is at least the double of the current atmospheric C pool (~760 Gt C; IPCC, 2001). Northern peatlands specifically are considered to account for 450 to 700 Gt (Gorham, 1991; Zimov et al., 2006; McGuire et al., 2008) of this amount, while the rest has been proposed to be stored in other soils than peatlands and deep alluvial sediments (Zimov et al., 2006; McGuire et al., 2008). Concern has been raised whether these ecosystems will continue to be sinks of atmospheric C or if they will, or have already become C sources to the atmosphere. Temperatures in the Arctic regions have risen, causing thawing permafrost and exposure of previously stabile soil organic C for decomposition processes. A potential shift from C sink to atmospheric C source would in turn increase the atmospheric burden of greenhouse gases and provide a positive feedback on climate warming.

However, the atmosphere and biosphere C exchange data in the northern latitudes are few considering the large area that they aim to represent, and the uncertainty about the current C balance of northern peatlands is large. Some limitations behind the scarce data availability arise from logistical limitations in the Arctic. Long-term (multi-year to decadal) data sets that are needed to gain knowledge about temporal variability are also sparse and the spatial variation of soil properties, vegetation types and ecosystem structure is large which makes it difficult to scale up from plot scale to landscape scale level.

The C gas exchanges most frequently studied in the context of C budgets in northern peatlands are those of carbon dioxide (CO_2) and methane (CH_4). These studies have focused on the biologically active season and when conducted they are in most cases based on low temporal resolution data, i.e. days to weeks between sampling (Crill et al., 1992; Klinger et al., 1994; Oechel et al., 1995, 2000a; Heikkinen et al.,

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2002b; Heyer et al., 2002; Turetsky et al., 2002; Treat et al., 2007). While the CO_2 exchange is controlled by the balance of plant photosynthesis and remineralization processes, the CH_4 surface exchange is determined by its production and consumption rates and transport processes in the soil profile (Joabsson et al., 1999). Very few studies have presented year around data for annual C balance budgets including both the CO_2 and CH_4 exchange from subarctic/Arctic environments. Many studies do not have any winter measurements, and annual C balance budgets of CO_2 and CH_4 exchange commonly include some assumed/modeled winter data to estimate an annual budget (e.g. Alm et al., 1997; Oechel et al., 2000b; Heikkinen, 2003; Nykänen et al., 2003; Corradi et al., 2005). Annual C balance budgets based solely on either CO_2 (e.g. Aurela et al., 2002; Lund et al., 2007; Sagerfors et al., 2008) or CH_4 (Rinne et al., 2007, 2009) are somewhat more common. Modeling studies of the annual CO_2 and CH_4 exchange of these ecosystems exist (e.g. Frolking et al., 2002; Grant et al., 2003; Sitch et al., 2007) but the frequency of original field observations are highly insufficient, i.e. the validation of these models suffers from lack of data. As noted by recent studies, there is also a need for including non-methane volatile organic compound flux (NMVOCs) when studying the C budget of subarctic ecosystems (Tiiva et al., 2007; Bäckstrand et al., 2008a; Ekberg et al., 2008; Tiiva et al., 2008), which has not been done previously on a more continuous basis.

In this paper, we present an estimate of the annual net carbon gas balance (NCB) of a subarctic mire, based on semi continuous measurements of both CO_2 and total hydrocarbon flux (THC including CH_4 and NMVOCs) measurements, using data from both snow and snow free seasons, the latter herein referred to as green season. Assumed snow season fluxes during a period with missing data has been adopted for the annual budget estimation. This study does not include the dissolved organic and inorganic C (DOC and DIC) and particulate organic C (POC) components of the Stordalen mire C budget. However, these components are of course necessary to do a full C budget and estimates of their exchange rates are presently under investigation by other research groups working at the mire.

The Stordalen mire, where the study has been conducted, is characterized by discontinuous permafrost which creates an environment with distinct differences in moisture and permafrost regimes as well as trophic status (Rosswall et al., 1975), which in turn drives a diverse vegetation distribution (Malmer et al., 2005). We have measured the C gas exchange at three localities that reflect the range of plant species distributions typical for three levels of moisture, nutrient and permafrost status found at the mire. The annual net C gas budget presented is based on six years of data (2002–2007), of which snow season data were collected in 2002, 2004, 2005 and 2007 while green season data were collected in all years (2002–2007) using an automatic chamber (AC) system for C gas flux measurements at time levels ranging from hours to years. Some of the data included in this paper have previously been published by Bäckstrand et al. (2008a; 2008b), but in those cases focus were on determining NMVOC contribution to THC as well as spatial and temporal controls on THC exchange during the growing seasons, whereas this paper combines CO_2 and THC exchange from both snow seasons and summer periods and estimates an annual C gas balance.

The Stordalen mire has been of environmental research interest for several decades. There are data available on plant community, permafrost distribution and C flux dynamics since the 1970s which have been compared to the state of the mire in the year of 2000 (Christensen et al., 2004; Malmer et al., 2005; Johansson et al., 2006). In these studies, focus was on the shorter green season C exchange and CO_2 data arrived to a lesser extent from continuously sampled data and CH_4 fluxes were manually sampled with low temporal resolution. This report is a continuation of the previous ones by expanding with another 3 years of high temporal resolution CO_2 fluxes as well as 6 years of high temporal resolution THC fluxes. In addition, an annual estimate can now be conducted by including data from the snow season not previously published. The change in permafrost distribution and plant communities have been important information to use when estimating how the C balance of the mire has changed over the decades and may change in the future.

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2 Materials and methods

2.1 Study site

The Stordalen mire is located in northern Sweden (68°22′ N, 19°03′ E), 10 km south east of Abisko and Abisko Scientific Research Station (ANS) (Fig. 1). The climate is subarctic with a mean annual temperature at ANS of 0.07°C with 308 mm of accumulated precipitation (20-year mean; 1986–2006). Stordalen is underlain by discontinuous permafrost, therefore localities nearby each other have a wide range of moisture and nutrient status which creates distinct differences in vegetation types (Malmer et al., 2005). Three distinct plant communities present at the mire are defined as those dominated by i) woody herbaceous vegetation on top of drained palsa areas (i.e. permafrost sites), ii) *Sphagnum* spp. and *Carex* spp. vegetation in the intermediate thaw features where the water table fluctuates close to the ground surface and iii) dense *Eriophorum angustifolium* in the wet areas where the ground thaws completely in the summer. These three plant communities were chosen for the study because they capture the range of moisture and nutrient status in the mire. Hereafter, they are referred to as the Palsa site, the *Sphagnum* site and the *Eriophorum* site. Further detailed description of the three sites can be found in Bäckstrand et al. (2008a,b).

Each site has differences in the active layer dynamics (AL; the top layer of the soil above the permafrost that freezes and thaws each year) and the water table position (WT). Figure 2 shows the variation over an example year (2004) for AL and WT between the three sites as well as temperature and precipitation recorded at ANS.

2.2 Automatic chamber measurements of CO_2 and THC flux

The automatic chamber system used to measure the CO_2 and THC exchange has previously been described in detail (Bäckstrand et al., 2008a; Bäckstrand et al., 2008b). Briefly, is consists of 8 transparent Lexan® chambers positioned at the three sites (3 chambers at the Palsa site, 3 chambers at the *Sphagnum* site and 2 chambers at

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the *Eriophorum* site). Each chamber covers an area of 0.14 m^2 (38 cm×38 cm) with a height from 25–45 cm depending on the vegetation and depth of insertion. A lid is closed and opened automatically with a double acting pneumatic piston (Bimba Manufacturing Company, Illinois, USA) connected to a compressor (GAST Manufacturing Inc., Michigan, USA) by 1/8″ nylon tubes. Each chamber was closed for 5 min every 3 h. The chambers were connected to the associated analysis system, placed in a nearby heated cabin, by 3/8″ Dekoron polypropylene lined and sheathed aluminum tubing through which air was circulated at a rate of 4 L min^{-1} during sampling. Sample air was circulated through a condensing water trap, a 0.4 µm particle filter and then the air passed through a non-dispersive CO_2 analyzer. A flow of 1–5 mL min^{-1} was drawn to the THC analyzer from the closed, main sample flow. Raw signals were acquired with a datalogger (CR10X Campbell Scientific Inc., Utah, USA) at a frequency of 3 s and averaged every 15 s. THC and CO_2 fluxes were calculated using a linear regression of change in the headspace mixing ratio with time during a period of 2.5 min.

2.3 Data coverage for specific years

The data coverage for specific years is shown in Table 1. The table shows first and last day of sampling for each year. In between these days, there may be shorter or longer periods with no data collection. The number of days during the sampling period that are represented in the data set are accounted for as % coverage in Table 1.

2.4 Environmental variables

Active layer depth and water table position relative to ground surface that is presented in Fig. 2 were measured manually 3–5 times per week at all sites during the green season. Year around meteorological data of temperature and precipitation presented in Fig. 2 were recorded at ANS. Comparing the annual average temperature at Stordalen with that recorded at ANS, Stordalen is consistently ∼1°C cooler (Jackowicz-Korczyñski et al., 2009).

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2.5 Data analyses

We define the net carbon gas balance (NCB) as the sum of the oxidized (CO_2) and the reduced (THC; CH_4 and NMVOCs) C compound gas fluxes. To calculate the NCB, both flux estimates of CO_2 and THC fluxes are needed. There are more CO_2 data than THC and therefore, the occasions when NCB has been possible to calculate are in the range of THC data points. Any potential exchange between land and atmosphere of carbon monoxide (CO) has not been captured by our measurements. A natural exchange between wetland environments and land can be present both as uptake and emission (Funk et al., 1994; Rich and King, 1998), but this gas component cannot be measured by the CO_2 and THC analyzers adopted at our site.

Running means for CO_2 and THC individual flux observations of approximately 3 d are calculated for each year separately (Fig. 3). They are based on 72 data points at the Palsa and *Sphagnum* sites (where 3 chambers are distributed at each site) and 48 data points at the *Eriophorum* site (where 2 chambers are positioned), where one data point represent an individual chamber flux measurement.

When yearly accumulated fluxes were calculated, we filled periods of missing data in the early (days 1–84) and late (days 342–365) year with snow season averages from Table 2. Because the data coverage is different for different years (Table 1), accumulated fluxes have been calculated by sorting all data from all years by time and day of year, independent on what year it was collected. By this approach, which incorporates the interannual variability into the mean, we create the longest period of data coverage in order to develop an average estimate based on several years of observations. Because the data coverage from each separate year sometimes differ from each other, it is not possible to explore the interannual variability over as long time periods as a year. The interannual variability of the green season THC fluxes has been discussed previously (Bäckstrand et al., 2008b).

In the case of the wet CH_4 emitting sites, a global warming potential (GWP) factor of 25 (i.e. a 100 year perspective; Forster et al., 2007) has been used to estimate the

THC emission as well as NCB in CO_2 equivalents. It should be noted that only the average CH_4 component of the THC flux at each site has been transformed into CO_2 equivalents and the rest considered to be NMVOCs has not been assigned any GWP factor (approximately 25% NMVOCs of THC at the *Sphagnum* site and 15% NMVOCs at the *Eriophorum* site on average in the green season; Bäckstrand et al., 2008a; 2008b). NMVOCs do have an indirect impact on the concentration of greenhouse gases and can be assigned a GWP factor according to IPCC (Forster et al., 2007). However, because of the uncertainties in these numbers and because of the fact that we have not specified specific NMVOC species in this study, we have chosen not to assign any GWP to the NMVOC component of THC. Further, the GWP of 25 has been applied to fluxes throughout the year even though the NMVOC contribution to THC likely can be considered close to zero during the snow season. However, because we have not estimated NMVOC contribution to THC for the snow season fluxes, we again chose to calculate the radiative forcing impact in a conservative way.

Definition of snow season (days 1–118 and 289–366) and green season (119–288), respectively has been conducted using a digital camera (visible part of the spectrum) at Stordalen. One photograph per day was taken through out the years (Svensson, 2004; Jackowicz-Korczyñski et al., 2007, 2009). This results in an approximate snow season of 194 d while the green season is 171 d, i.e. 23 d longer snow season compared to green season. Because the division of the seasons is based on a larger scale picture of whether the mire was snow covered or not, it does not reflect the spatial variation of snow accumulation within the mire. The spatial variation is large and in general, it can be considered that the palsas most often are bare due to snow drift caused by wind, while the topographically lower positioned *Sphagnum* and *Eriophorum* sites are characterized by higher rates of snow accumulation. General snow depths have been reported to range between 0 and 10 cm on top of the palsas and between 10 and 60 cm in the deeper parts (Rydén and Kostov, 1980).

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3 Results

3.1 Seasonal dynamics of C gas flux components

Individual chamber measurements of CO_2 and THC have been plotted as 3 d running mean, each year plotted separately (Fig. 3). Calculated NCB, for those chamber closure times when both CO_2 and THC were measured, are presented as individual data points. The number of flux measurements used in the analysis were 12 677 and 6301 for CO_2 and THC, respectively at the Palsa site, 25 493 (CO_2) and 12 733 (THC) for the *Sphagnum* site and 8959 (CO_2) and 4945 (THC) for the *Eriophorum* site.

We analyzed the differences between the snow season fluxes and the fluxes measured during the green season (Table 2; Fig. 3). In the snow season, all sites were on average C sources of both CO_2 and THC to the atmosphere, therefore the NCB was also positive, i.e. there was on average a net C input to the atmosphere. The average snow season CO_2 and THC flux at the Palsa site were 292 mg C m^{-2} d^{-1} and 0.453 mg C m^{-2} d^{-1}, respectively. Corresponding fluxes at the *Sphagnum* site were 73.1 mg C m^{-2} d^{-1} for CO_2, and 11.5 mg C m^{-2} d^{-1} for THC. For the *Eriophorum* site, snow season averages were 211 mg C m^{-2} d^{-1} for CO_2 and 78.2 mg C m^{-2} d^{-1} for THC. In contrast, all sites were on average sinks of CO_2 and sources of THC in the green season. Due to a stronger CO_2 sink function, the average NCB was negative, i.e. an average loss of C from the atmosphere as opposed to the snow season. The Palsa site had an average net uptake of CO_2 that corresponds to −184 mg C m^{-2} d^{-1}, while the average THC emission was 2.01 mg C m^{-2} d^{-1}. At the *Sphagnum* site, the average CO_2 sink function was greater representing an uptake of −318 mg C m^{-2} d^{-1}, and also the average THC emission was greater, 28.1 mg C m^{-2} d^{-1}. The highest average CO_2 uptake and the highest average THC emission were both found at the *Eriophorum* site, −652 mg C m^{-2} d^{-1} and 119 mg C m^{-2} d^{-1}, respectively.

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3.2 Annually accumulated estimates of C gas flux components

Annually accumulated fluxes were estimated for each site, for which we filled periods of missing data in the early (days 1–84) and late (days 342–365) year with snow season averages arrived from Table 2 (Fig. 4; Table 3). The length of the growing season, i.e. the period during which there is a continuous net CO_2 uptake according to the accumulated fluxes, varied between the sites (Fig. 4). The Palsa site had a 110 day long growing season, starting on day 124 and ending on day 234. The *Sphagnum* site had a longer growing season of 134 d lasting between day 118 and 134. At the *Eriophorum* site, the growing season was the shortest with 103 d, starting later than at the other sites on day 154 and lasting until day 257.

The whole year accumulated fluxes showed that the Palsa site was a source of CO_2 by 30 g C m^{-2} and also a small source of THC by 0.52 g C m^{-2}. Because the THC component was very small compared to the CO_2, the NCB was positive and in the same range as CO_2. This means that the Palsa site added C to the atmosphere over a year's time span (Table 3; Fig. 4a). The *Sphagnum* site was a C sink of CO_2 by −35 g C m^{-2} while being a C source of THC by 6.2 g C m^{-2}, but since the CO_2 sink was stronger than the THC source, there was a negative NCB of −29 g C m^{-2}. This means that the *Sphagnum* site takes away C from the atmosphere on an annual basis (Table 3; Fig. 4b). The *Eriophorum* site was a C sink for CO_2 by −35 g C m^{-2} from the atmosphere and at the same time it was a C source of THC by 32 g C m^{-2}. At the *Eriophorum* site, the C sink strength of CO_2 was in a similar range as the C source strength of THC, however slightly stronger, and the NCB was therefore close to balanced by −3.1 g C m^{-2}, therefore representing a small sink of atmospheric C over the course of a year (Table 3; Fig. 4c).

In Table 3, the seasonal contribution to the absolute sum of the annual flux for each of the C components is presented. In a similar way to the overall seasonal averages presented above, the results show that the snow season efflux of CO_2 has a very strong impact on the annual NCB, but also that the accumulated THC emission during

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the snow season contribute significantly to the annual THC efflux.

The amount of C as THC that is exchanged at the surface is often low compared to the mass of C as CO_2. On the other hand, in terms of CO_2 equivalents, the CH_4 component which represents the larger part of THC at the wetter *Sphagnum* spp. (75%) and *Eriophorum* spp. (85%) vegetation communities at Stordalen has a strong warming potential in the atmosphere. The CH_4 component is therefore important when considering an ecosystem's total short term radiative forcing capacity on climate. On a 100 year time span, CH_4 is considered to have a 25 times more effective radiative forcing potential than CO_2 (Forster et al., 2007). This result in the annual NCB at the *Sphagnum* and *Eriophorum* site shifting from being sinks of C measured in $g\,C\,m^{-2}$ to becoming much stronger atmospheric sources of C as CO_2 equivalents and thereby also exerting a warming effect on climate (Table 3).

3.3 Whole mire C gas balance

Each vegetation community's annually accumulated flux per unit area is important to compare the flux ranges between different plant types and their physical environment, such as different moisture regimes and the presence or absence of permafrost. This comparison enables us to estimate how dynamic environmental changes such as disappearance of permafrost and shifted hydrological regimes might affect the C exchange. Extrapolating the plot scale measurements to estimate the whole Stordalen mire C fluxes require area estimates of each vegetation community.

The mire has a total area of 16.5 ha. Each vegetation type's area distribution on the mire was determined in 2000 (Table 4) (Malmer et al., 2005; Johansson et al., 2006). The Palsa, *Sphagnum* and *Eriophorum* sites have been estimated to cover 8.3 ha, 6.2 ha and 2 ha, respectively (when the class Semiwet and Wet in Johansson et al., 2006b corresponds to the *Sphagnum* site in this study). By using the area estimates from these previous studies as Stordalen and combining them with the C fluxes measured in this study, the annual C gas exchange from the whole mire was estimated. It was calculated that the whole mire is a sink of CO_2 by −425 kg C ($-2.6\,g\,C\,m^{-2}$) and

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a source of THC by 1063 kg C (6.4 g C m^{-2}). Consequently, the calculations indicate that the mire is a net source of C to the atmosphere by 639 kg C (3.9 g C m^{-2}) per year (Table 5). This means that the reduced C flux was sufficient to shift the mire from a sink to a source of C to the atmosphere over a year's time span.

By using area estimates of the mire vegetation distribution from 1970 as well as in 2000 (Johansson et al., 2006) (Table 4), it is possible to calculate a whole mire annual C gas budget and analyze how it has changed over the decades (Table 5). Regarding the NCB of the mire, it was estimated that the mire was a net C source by 990 kg C in 1970 and this source strength had decreased to 639 kg C by the year of 2000. Behind this decrease in source strength, we found increased net uptake of CO_2. But there was also an increased net emission of THC and because the increase in THC consists mostly of CH_4, the mire's radiative forcing capacity on climate has also increased substantially. When we take into account the GWP_{100} of the CH_4 component of THC, we calculate that the mire's annual source function of net radiative forcing on climate increased by 21% over the three decades.

4 Discussion

4.1 Seasonal dynamics of C gas flux components

The most significant difference in the C flux dynamics when comparing the snow and green seasons were found relating to the CO_2 dynamics. On average, as expected, we found positive fluxes of CO_2 (i.e. emission) in the snow season and uptake in the green season (Tables 2 and 3). Analyzing the standard deviations, it is found that the variability is greater in the green season reflecting the more pronounced diurnal variation including high photosynthetic rates during the day and more pronounced respiration during the night. In contrast, the variability in the snow season fluxes is less, likely because of cold temperatures and less diurnal variation in lower light regimes at these high latitudes. The differences in THC emissions between the two seasons are

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not as pronounced as for CO_2 (Tables 2, 3). There is higher THC efflux in the green season compared to the snow season, again as expected. Factors such as higher temperatures, moisture and carbon substrate availability have previously explained higher emissions as well as spatial variability between vegetation communities in the THC emission rates (Ström and Christensen, 2007; Bäckstrand et al., 2008b). While the green season accounts for the highest THC flux, it is still important to notice the relatively high emissions in the winter.

While comparable growing season daily flux magnitudes previously have been reported between Stordalen and other sites (Christensen et al., 2004; Johansson et al., 2006; Bäckstrand et al., 2008b), it can now as well be concluded that the winter fluxes measured at Stordalen also are comparable with other winter fluxes of oxidized and reduced C compounds measured at similar locations. Regarding average CO_2 fluxes in the snow season measured at Stordalen, these ranged between 73.1 and 292 $mg\,C\,m^{-2}\,d^{-1}$, with highest efflux at the Palsa site and lowest efflux at the *Sphagnum* site. This is a large variation between vegetation communities located nearby each other, and other studies reinforce the difficulties in projecting CO_2 fluxes in the winter by showing a wide range of average daily fluxes. At a tundra wetland near Vorkuta, Russia, the reported range in wintertime CO_2 flux was 14–27 $mg\,C\,m^{-2}\,d^{-1}$ (Heikkinen et al., 2002a), at the boreal mire Degerö Stormyr in northern Sweden the range was between 38 and 54 $mg\,C\,m^{-2}\,d^{-1}$ (Sagerfors et al., 2008) and in eastern Finland at several bog and fen sites, the efflux ranged from 167 to 478 $mg\,C\,m^{-2}\,d^{-1}$ (Alm et al., 1997; Alm et al., 1999). On the subarctic flark fen in Kaamanen, northern Finland, the average wintertime CO_2 flux was presented as 130 $mg\,C\,m^{-2}\,d^{-1}$ (Aurela et al., 2002) and at the boreal peatland Mer Bleu, Canada, the same number is around 390 $mg\,C\,m^{-2}\,d^{-1}$ (Roulet et al., 2007).

Regarding the reduced C compound fluxes, the wetter sites at Stordalen had average snow season THC fluxes of 11 $mg\,C\,m^{-2}\,d^{-1}$ and 78 $mg\,C\,m^{-2}\,d^{-1}$, respectively for the *Sphagnum* and *Eriophorum* site sites (Table 2) and these are also comparable to other sites' measurements. At bogs and fens in Finland, winter CH_4 measurements revealed fluxes between 4 and 17 mg C m^{-2} d^{-1} (Alm et al., 1999). At a tundra wetland near Vorkuta, Russia, the winter fluxes of CH_4 were in the range 11 mg C m^{-2} d^{-1} to 48 mg C m^{-2} d^{-1} (Heikkinen et al., 2002a). Vaisjeäggi in Finland had lower CH_4 fluxes around 5 mg C m^{-2} d^{-1} (Nykänen et al., 2003) while the minerotrophic fen Siikaneva had winter fluxes reaching up to 24 mg C m^{-2} d^{-1} (Rinne et al., 2007). A likely possible explanation to the relatively high THC emissions in the winter is continuous CH_4 production, however small, and degassing of CH_4 from deeper peat layers that are not frozen. Earlier studies at Stordalen and the thaw-freeze cycles at the mire have shown that the frost front starts at the peat surface around October and deepens during the winter, but it rarely reaches the permafrost layer in the intermediate thaw sites at the mire (Rydén and Kostov, 1980). In areas where there is no permafrost, the ground still freezes from the top and downwards from the beginning of the winter. Also here, there is a potential thick layer of unfrozen peat that can support continuing methanogenesis and degassing during winter. The onset, depth and maintenance of snow cover will be critical to the peat frost dynamics and will play an important role in interannual variability of the fluxes.

It can be hypothesized that the snow season's importance for the annual C budget is greater at peatland locations located at high latitudes where there is a shorter green season and longer snow season. Because of the significant snow season emissions, it is recommended that this season is considered as important as the green season regarding measurement campaigns. By excluding this period from the annual budgets, an underestimation of the peatlands' C source strength is likely. The fact that other studies show snow season emission of CO_2 and CH_4 that is comparable with our measurements gives support for the use of our snow season averages to gap fill periods during which no data collection were made.

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4.2 Annually accumulated estimates of C gas flux components

There are only few estimates of annual C gas budgets around the Arctic that includes both CO_2 and hydrocarbon components (either or both CH_4 and NMVOCs). The studies that have been presented also show large variation and there are, as always, limitations in the data sets because of missing winter periods and different ways of gap filling. However, a comparison among this study at Stordalen and other estimates of the annual C gas balance reveals some significant patterns. Table 6 illustrates that all sites that show positive annual NCB, meaning that they are sources of C to the atmosphere on an annual basis, are palsa or hummock areas. Among the examined studies, the net C source strengths reach 30 g C m^{-2}. Among the sites that are net C sinks, ranging from an uptake of −2 g C m^{-2} to an uptake by −139 g C m^{-2}, are all characterized by being wet peatland/vegetation types. In these environments, the CH_4 component is very important. When compared to the net amount of C exchange (both CO_2 and CH_4), the CH_4 component accounts for 15–48% (the Stordalen mire estimate excluded). The only study where the NCB is positive as a result of higher net THC emissions than net CO_2 uptake is at the Stordalen mire. The area weighted yearly accumulated fluxes from the whole mire (16.5 ha) resulted in a positive annual NCB, a release of C to the atmosphere at about 3.9 g C m^{-2}, based on a net uptake of CO_2 by −2.5 g C m^{-2} and an emission of THC by 6.4 g C m^{-2} (Table 3). The factor behind this differential relationship between CO_2 and THC at Stordalen compared to the other sites seems to be that the net CO_2 uptake is much lower at Stordalen compared to other sites, while the CH_4/THC emissions are more similar between sites. Differences in productivity between sites can however not be explained in any simply way such as for example latitudinal position and consequently length of growing season. Other sites are positioned as north, and the climate conditions between the sites vary and cannot be compared by simple means like reviewing literature. Differences in productivity may be due to different area distributions and density of specific vegetation communities. However, from the comparison between the studies presented in Table 6, one can con-

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clude that it is only in the wetter, often more nutrient rich mire/vegetation types that the amount of CH_4/THC (in weight C measured) had a significant impact on the NCB.

The results of the C fluxes measured with the automatic chambers at Stordalen can now also be compared to CH_4 fluxes measured with an eddy covariance (EC) system at the same mire (Jackowicz-Korczyñski et al., 2009). Taking into account wind conditions and vegetation class coverage, it was possible for the EC system to derive the emission signal originating form the *Sphagnum* and *Eriophorum* vegetation type communities. To avoid comparing time periods with scarcer data density (i.e. assumed and modeled data in the winter time), the summer period between days 154 and 249 was chosen for comparison between the two methodologies because of the high data density from both studies. During this period, the EC tower recorded CH_4 emissions of 9 g C m^{-2} (Jackowicz-Korczyñski et al., 2009). By applying the accumulated fluxes from the chamber data to the vegetation community areas arrived from the tower footprint, it results in area weighted accumulated CH_4 flux of 5 g C m^{-2} for the same period (6 g C m^{-2} of THC). The most probable reason for the difference is that the EC measurements capture larger amounts of CH_4 ebullition from the wettest fen part of the mire. Ebullition has been shown to support a large amount of CH_4 emitted from wetland and lakes (Christensen et al., 2003; Bastviken et al., 2004; Walter et al., 2006, 2007), but the automatic chamber system cannot capture these fluxes. It is also likely that the tower capture higher emissions during windy conditions compared to the chambers, a factor that has been documented in these and other studies (Wille et al., 2008; Jackowicz-Korczyñski et al., 2009).

4.3 Thawing permafrost, resulting vegetation changes and their implications on the annual C gas balance

The vegetation changes that have occurred at Stordalen over the last decades as a result of thawing permafrost are characterized by receding palsa areas and increased wetter vegetation communities (Malmer et al., 2005). These changes in vegetation and the physical environment consequently have implications for the whole mire C dynamics. Some of these flux changes have been presented before based on less frequently collected manual data and focusing on the growing season (Christensen et al., 2004; Johansson et al., 2006). This study can be seen as complement to and an update of former studies, particularly for the one by Johansson et al. (2006), now incorporating more years of data (including higher frequency measurements of the reduced C compounds), as well as taking into account the longer snow season period with much lower air temperatures. In a similar way to Johansson et al. (2006), we assume that the annual C exchange from a specific subhabitat has not changed over time, which makes it possible to use the same exchange rates per unit area. The uncertainties for our results also lie in the preciseness in the area distribution for each vegetation community, as the mire is very heterogeneous with respect to plant types and environmental factors.

We find that the whole mire has had an increased CO_2 uptake in 2000 compared to 1970 (Table 5). In 1970, the annual CO_2 exchange was estimated to be positive, 157 kg C, but with the subhabitat distribution measured in 2000, the whole mire is calculated to be a net sink of CO_2 by −425 kg C. The change represent an almost 3 times stronger CO_2 sink function than the source strength in 1970. This is due to the calculated expansion of thawed peat areas similar to the *Sphagnum* and *Eriophorum* subhabitats which are more productive during the growing season than the palsas, thereby increasing the ecosystem's capacity for CO_2 uptake. Also, the respiration during the winter is less at the *Sphagnum* and *Eriophorum* site, and higher at the palsa site, further amplifying the possibility for an overall negative CO_2 flux at the mire. According to our results, the vegetation changes have also brought increased THC emissions by 230 kg C per year, representing an increase of 28% (Table 5). Both the *Sphagnum* and *Eriophorum* sites are high THC emitting environments, while the Palsa is not. In conclusion, it was estimated that the mire was a net source of C three decades ago, and still is today, but the total C source function has decreased by 35% (Table 5). In contrast, the mire's NCB in CO_2 equivalents has increased net radiative forcing on climate by 21%.

The 16% increase in the mire's CO_2 sink function over the three decades that was found for the 153 d long growing season in the previous study (Johansson et al., 2006) has then been confirmed, now based on the annual estimates from this study (from 0.95 g C m^{-2} in 1970 to −2.6 g C m^{-2} in 2000). The even higher strength in the sink function that is seen in the annual numbers when going from 1970 to 2000 is likely to be due to the incorporation of the snow season flux data. In the snow season, all sites are on average sources of CO_2 to the atmosphere, and also annually, the Palsa site is a CO_2 source. Therefore, the decrease in area extent of an annual CO_2 source (palsa areas) in favor for vegetation communities being annual CO_2 sinks (wetter areas) lead to this shift from the mire being a source of CO_2 in 1970 to a sink of CO_2 in 2000. The two studies further confirm that the estimates of increased reduced C compound emissions are similar, 22% and 28% for the growing season and annual budget, respectively. When comparing the estimates for increase in radiative forcing on the atmosphere, which is 47% accounting for the growing season (Johansson et al., 2006) and 21% for the annual budget (this study), the difference is likely to be due to the fact that the CH_4 component as CO_2 equivalents get a higher impact when analyzed over only the growth period as compared to on annual basis.

Concerning the whole mire budgets presented for Stordalen in this study, it should be considered that the calculations are based on vegetation community distributions in 1970 and 2000. Because it is now nearly a decade later, 2008, and a continuous collapse of palsa margins can be detected from year to year along with deepened hollows in the palsa ridges, it is very much likely that the expansion of the wetter areas have continued and that the palsa areas have receded even more. This implies a likelihood of that the mire's productivity and net CO_2 uptake have increased along with the expanding wetter areas, but also that the mire's radiative forcing on climate has intensified along with the high rates of CH_4 emissions.

Beyond the scope of this paper but closely related to the changes in the C gas dynamics as a result of the receding palsas, are likely changes in the export of DIC,

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DOC and POC (Jonsson et al., 2003; Guo et al., 2004; Roulet et al., 2007; van Dongen et al., 2008). The export of DOC may potentially increase as permafrost thaws and releases DOC into the hydrological system. Collapsing palsa margins, suddenly and in potentially very large amounts, increase the erosion derived concentration of POC. Both DIC, DOC and POC export contribute to the diminishing of the total mire C stock, and it is important to incorporate these components in the total mire C budget. This also includes incorporating the surrounding lake and river fluxes to understand where in the system these C components will go in the future, for example being deposited in the sediments on the lake bottom or decomposed within the lakes and emitted as CO_2 or CH_4 from the lake surfaces. Terrestrial C export at Stordalen for the year of 2005 has been estimated to 9.5 $g\,C\,m^{-2}$, where approximately half of this is estimated to be emitted from the lake surface as CO_2 and/or CH_4, i.e. approximately 5 $g\,C\,m^{-2}$ lake surface and year (J. Karlsson, personal communication, 2008). Other studies report DOC/DIC export rates between 5 and 15 $g\,C\,m^{-2}$ at similar environments (Alm et al., 1997; Heikkinen et al., 2002a; Roulet et al., 2007). If we apply the annual terrestrial C export number of 9.5 $g\,C\,m^{-2}$ as determined from Stordalen studies and the lake Abborrtjärn (J. Karlsson, personal communication, 2008) to our area weighted NCB of the whole mire which is 3.87 $g\,C\,m^{-2}$, the annual loss from the mire is more than three times greater. By adding the net C emission from the lake surface of 5 $g\,C\,m^{-2}$ at Stordalen (J. Karlsson, personal communication, 2008), also having been identified at other lakes (e.g. Bastviken et al., 2004; Walter et al., 2007), the net loss from the mire and lake together is further reinforced.

5 Conclusions

Peatland environments are generally highly heterogeneous environments which creates large uncertainties when it comes to understanding the resulting effects of dynamic processes such as permafrost thaws in these areas. Different peatlands have shown to respond differently to thawing permafrost. For example, hydrological re-

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sponses have been highly variable between sites, sometimes causing drier (Billings et al., 1982; Oechel et al., 1995, 2000a) and sometimes causing wetter (Zuidhoff and Kolstrup, 2000; Jorgenson et al., 2001; Luoto et al., 2004) peatlands. This in turn exerts a strong control on plant community structure and C dynamics which clearly have been shown in this study and the comparison between the three sites with varying moisture and permafrost regimes. The uncertainties induced by the heterogeneity limit the scaling of plot scale data to ecosystem and global levels even to the point of having a common understanding of whether or not Arctic and subarctic peatlands can be considered to be consistent sinks or sources of C. However, this study among other estimates of specific peatlands net C balances, finds that these environments possibly are at, or near, a change in C balance. What we also can conclude from the Stordalen data, is that this specific mire has undergone environmental changes due to permafrost thaw which have had implications for the annual C balance, and most importantly, the net radiative forcing on climate. From our results, we can also point out the importance of wintertime measurements to fully understand the annual dynamics of the peatland C fluxes. The snow seasons can be important C source periods and by excluding this time of the year from the measurement campaigns, the C source strength of peatlands are possibly underestimated. Further, by showing that the reduced C compounds flux was sufficient to shift the whole mire from a sink to a source of C to the atmosphere over a year's time span, the importance of combining these C components for a better understanding of the C balance have been proven.

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Table 1. Sampling period for each year presented as day of year (DOY) for the first and last day of sampling. CO_2 and THC coverage indicates number of days in % when data are available during the sampling period. CO_2 and THC denote carbon dioxide and total hydrocarbon, respectively.

Year	Sampling period	CO_2 coverage (%)	THC coverage (%)
2002	84–147	100	97
2003	119–240	96	70
2004	147–329	100	51
2005	148–341	47	79
2006	123–234	86	25
2007	154–305	97	55

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Table 2. Statistics for flux data (mg C m^{-2} d^{-1}) from the snow season[a] and the greens season[a], each site analyzed separately. The reason why the mean NCB values are not simply the sum of CO_2 and THC in Table 2 is because the two gas components' mean values are based on different number of flux measurements. CO_2, THC, and NCB denote carbon dioxide, total hydrocarbons and net carbon gas balance, respectively.

		Snow season; Days 1–118/289–365					Green season; Days 119–288				
	C component	Mean flux	SD[b]	Min	Max	N[c]	Mean flux	SD[b]	Min	Max	N[c]
Palsa site	CO_2 mg C m^{-2} d^{-1}	292	551	−651	8831	2081	−184	1176	−6649	12 907	10 596
	THC mg C m^{-2} d^{-1}	0.453	2	−7	29	999	2.01	6	−9	113	5302
	NCB mg C m^{-2} d^{-1}	155	269	−496	1272	999	−177	1312	−6641	12 960	5300
Sphagnum site	CO_2 mg C m^{-2} d^{-1}	73.1	136	−501	1173	4159	−318	927	−31 713	5885	21 334
	THC mg C m^{-2} d^{-1}	11.5	6	−11	53	2047	28.1	17	0	119	10 686
	NCB mg C m^{-2} d^{-1}	81.2	166	−478	1185	2003	−325	969	−3848	3711	10 618
Eriophorum site	CO_2 mg C m^{-2} d^{-1}	211	750	−3987	5181	911	−652	2151	−12 430	30 996	8048
	THC mg C m^{-2} d^{-1}	78.2	32	13	234	212	119	76	0	636	4733
	NCB mg C m^{-2} d^{-1}	728	889	−1863	5294	190	−729	2246	−12 198	4640	4733

[a] Determined from camera at Stordalen (Svensson, 2004; Jackowicz-Korczyñski et al., 2009);
[b] Standard Deviation; [c] Number of data points.

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Table 3. The seasonal contribution[a] for each C component to the annual flux[b], in $g\,C\,m^{-2}$, separated into snow season, green season and annually. CO_2, THC, and NCB denote carbon dioxide, total hydrocarbons and net carbon gas balance, respectively.

	Snow season; Days 1–118/289–365			Green season; Days 119–288			Annually			
	CO_2	THC	NCB	CO_2	THC	NCB	CO_2	THC	NCB	NCB in CO_2 ekv.[c]
Palsa site	56	0.11	57	−27	0.41	−26	30	0.52	30	30
Sphagnum site	11	2.1	13	−46	4.1	−42	−35	6.2	−29	7.5
Eriophorum site	43	15	58	−78	17	−61	−35	32	−3.1	213

[a] Note that these numbers are arrived from the accumulated flux curves (Fig. 4), which in turn are based on data points when both THC and CO_2 flux measurements were available, i.e. in the range of the THC data points and not from the overall average fluxes presented in Table 2.
[b] For the Palsa and *Sphagnum* sites, CO_2 data was filled for day 1–84 and 330–365 while THC were filled for day 1–84 and 305–365. At the *Eriophorum* site, CO_2 data was filled for day 1–127 and 330–365 while THC data was filled for day 1–127 and 305–365.
[c] A GWP factor of 25 was used for the CH_4 component of THC (Forster et al., 2007).

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Table 4. Area estimates of vegetation type distribution at the mire (from Johansson et al., 2006b[a]).

Site	Area estimates (ha) 1970	2000	Δ (%)
Palsa	9.20	8.30	−10
Sphagnum	6.00	6.20	+3
Eriophorum	1.30	2.00	+54

[a] Sphagum site area in this study accounts for the two vegetation classes Semiwet and Wet in Johansson et al., 2006.

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Table 5. Yearly accumulated fluxes for the whole mire in kg C. Within brackets are whole mire area weighted fluxes in $g\,C\,m^{-2}$. The calculations are based on flux estimates from this study and area estimates from Johansson et al., 2006.

	Yearly accumulated fluxes from the whole mire in kg C ($g\,C\,m^{-2}$)			
C component	1970	2000	Δ (kg C)	
CO_2	157 (0.95)	−425 (−2.6)	−582	CO_2 uptake increase
THC	833 (5.1)	1063 (6.4)	230	THC emission increase
NCB	990 (6.0)	639 (3.9)	−351	decreased net C source function
NCB in CO_2 eqv.[a]	5990	7222	1232	increase in net radiative forcing

[a] A GWP factor of 25 was used for the CH_4 component of THC (Forster et al., 2007).

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Table 6. Compilation of annual net carbon balances (NCB in $g C m^{-2}$) for subarctic mires where the exchange of both CO_2, CH_4 and sometimes NMVOCs and DOC/DIC leaching are represented in the C balance estimation. All units in $g C m^{-2}$. If the CO_2 and CH_4 components are not specified in the table, this information could not be revealed from the specific reference.

Mire/vegetation type	Location	Long/Lat	Method[a]	CO_2	CH_4	NCB	References
Boreal oligotrophic fen	Siikaneva, Finland	61°50′ N, 24°12′ E	EC	−43	9	−33	Rinne et al., 2007
Low sedge pine fen	Salmisuo, Finland	62°47′ N, 30°56′ E	SC	−98	30	−68	Alm et al., 1997[b]
Mesotrophic subarctic fen	Kaamanen, Finland	69°08′ N, 27°17′ E	EC	−18	11	−7±5	Aurela et al., 2002[c]
Tundra wetland, hummocks	Vorkuta, Russia	67°23′ N, 63°22′ E	SC			8	Heikkinen et al., 2002a[d]
Tundra wetland, flarks/lawns	Vorkuta, Russia	67°23′ N, 63°22′ E	SC			−2 to −36	Heikkinen et al., 2002a[d]
Arctic wet tussock grassland	Kolyma river, Russia			−38	12	−26	Corradi et al., 2005[e]
Mixed mire	Stordalen, Sweden	68°22′ N, 19°03′ E	AC	−3	6	4	This study[f]
Mixed mire, Palsa site	Stordalen, Sweden	68°22′ N, 19°03′ E	AC	30	1	30	This study[f]
Mixed mire, *Sphagnum* site	Stordalen, Sweden	68°22′ N, 19°03′ E	AC	−35	6	−29	This study[f]
Mixed mire, *Eriophorum* site	Stordalen, Sweden	68°22′ N, 19°03′ E	AC	−35	32	−3	This study[f]
Mixed mire	Stordalen, Sweden	68°22′ N, 19°03′ E	EC	−89	20	−69	Jackowicz-Korczyñski et al.[g]
Palsa mire, wet surfaces	Vaisjeäggi, Finland	69°49′ N, 27°10′ E	SC			−37 to −139	Nykänen et al., 2003
Palsa mire, palsa with shrubs	Vaisjeäggi, Finland	69°49′ N, 27°10′ E	SC	−19 to −53	1	−18 to −52	Nykänen et al., 2003
Palsa mire, palsa no shrubs	Vaisjeäggi, Finland	69°49′ N, 27°10′ E	SC			sources	Nykänen et al., 2003[h]

[a] Method as indicated: EC (eddy covariance), SC (static chambers), AC (automatic chambers).
[b] CH_4 estimate includes DOC/DIC leaching by $8 g C m^{-2}$.
[c] CH_4 estimate includes DOC/DIC leaching.
[d] Includes a loss of DOC/DIC leaching by $5 g C m^{-2}$.
[e] CH_4 emissions assumed only in July and August.
[f] CH_4 estimate includes NMVOCs.
[g] CO_2 flux estimate is a seven year average (2001–2007) while CH_4 flux is a two year average (2006–2007). Manuscript submitted.
[h] Source strength not specified.

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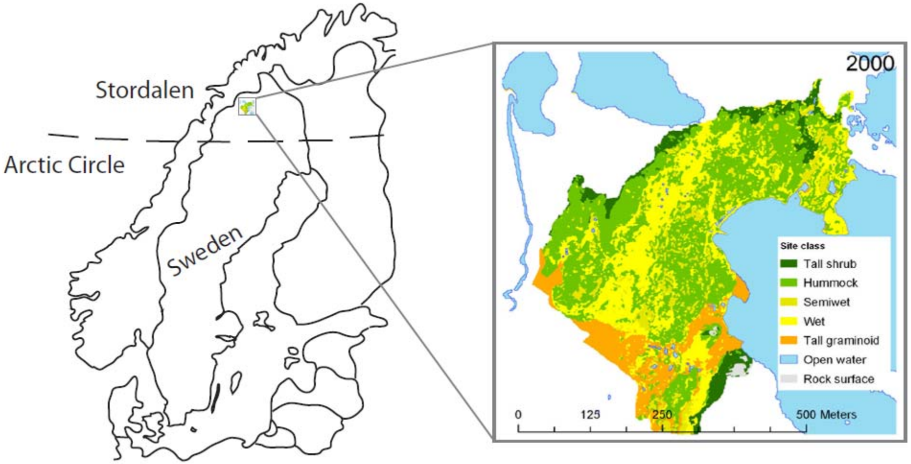

Fig. 1. Location map showing the position of the Stordalen mire in northern Sweden (68°22′ N, 19°03′ E) and also a vegetation map illustrating the highly variable plant community distribution at the mire (from Malmer et al., 2005). The Hummock class in the vegetation map corresponds to the Palsa site in this study, whereas the Semiwet and Wet classes corresponds to *Sphagnum* site and Tall graminoid class corresponds to *Eriophorum site*.

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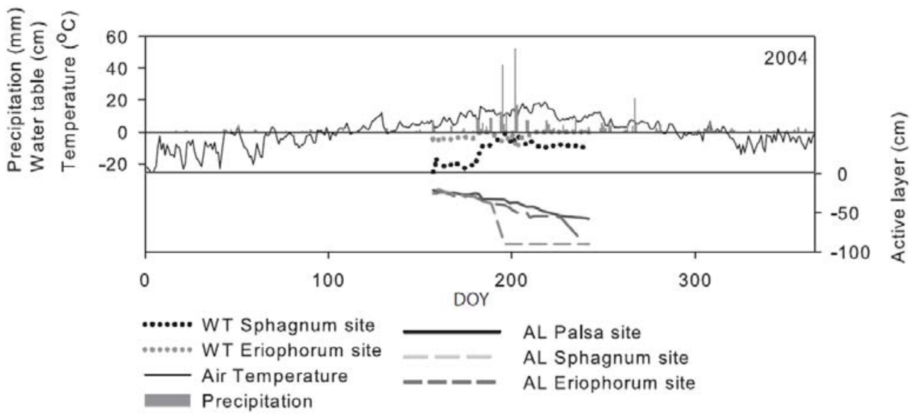

Fig. 2. One year of environmental parameters of water table (WT) and active layer (AL) show the differences in moisture and permafrost regimes at the three sites (Palsa, Sphagnum and Eriophorum) in the summer season. The annual temperature curve and precipitation data were collected at Abisko Scientific Research Station. DOY on the *x* axes stands for day of year.

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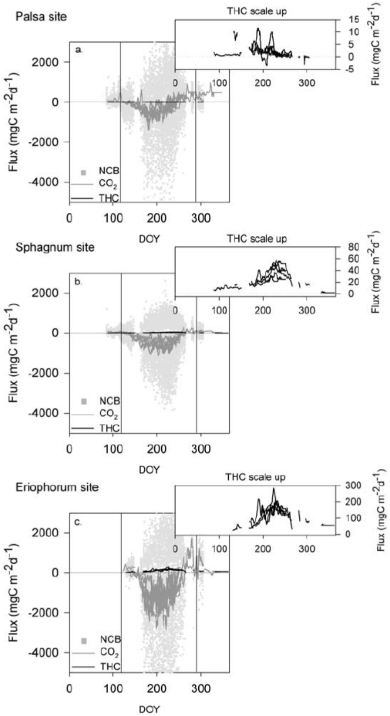

Fig. 3. Three day running mean of CO_2 and THC presented as lines, and NCB (sum of CO_2 and THC) estimates are presented as individual data points. Because the THC component measured in gram C is very small compared to CO_2, the seasonal distribution of the NCB measurement points can be considered to also show the large scale seasonal variation for CO_2. Positive numbers represent addition to the atmosphere and negative numbers represent loss from the atmosphere. The time period between vertical lines at DOY 119 and DOY 289 indicate the limit of the green season. DOY on the *x* axes stands for day of year. All fluxes in $mg\,C\,m^{-2}\,d^{-1}$.

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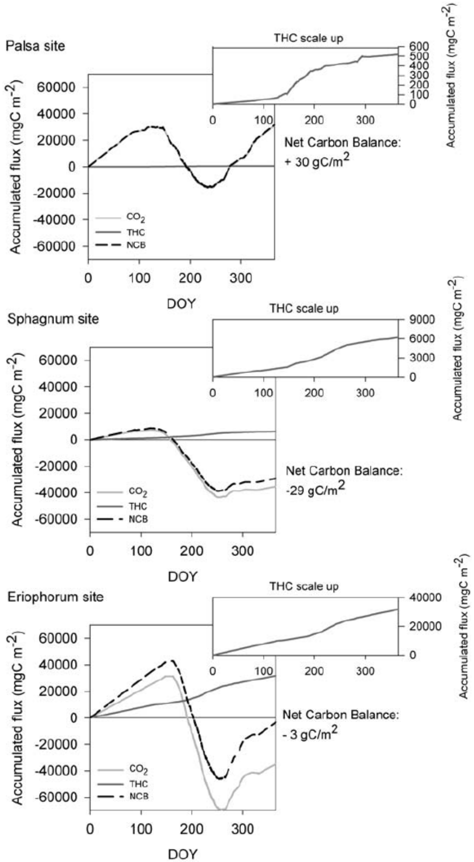

Fig. 4. Accumulated fluxes of CO_2, THC and NCB where each site is presented separately. Positive numbers represent addition to the atmosphere and negative numbers represent loss from the atmosphere. DOY on the *x* axes stands for day of year. All fluxes in $mg\,C\,m^{-2}$.