A catchment-scale carbon and greenhouse gas budget of a subarctic landscape

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This is the first attempt to budget average current annual carbon (C) and associated greenhouse gas (GHG) exchanges and transfers in a subarctic landscape, the Lake Torneträsk catchment in northern Sweden. This is a heterogeneous area consisting of almost 4000 km² of mixed heath, birch and pine forest, and mires, lakes and alpine ecosystems. The magnitudes of atmospheric exchange of carbon in the form of the GHGs, CO₂ and CH₄ in these various ecosystems differ significantly, ranging from little or no flux in barren ecosystems over a small CO₂ sink function and low rates of CH₄ exchange in the heaths to significant CO₂ uptake in the forests and also large emissions of CH₄ from the mires and small lakes. The overall catchment budget, given the size distribution of the individual ecosystem types and a first approximation of run-off as dissolved organic carbon, reveals a landscape currently with a significant sink capacity for atmospheric CO₂. This sink capacity is, however, extremely sensitive to environmental changes, particularly those that affect the birch forest ecosystem. Climatic drying or wetting and episodic events such as insect outbreaks may cause significant changes in the sink function. Changes in the sources of CH₄ through increased permafrost melting may also easily change the sign of the current radiative forcing, due to the stronger impact per gram of CH₄ relative to CO₂. Hence, to access impacts on climate, the atmospheric C balance alone has to be weighed in a radiative forcing perspective. When considering the emissions of CH₄ from the mires and lakes as CO₂ equivalents, the Torneträsk catchment is currently a smaller sink of radiative forcing, but it can still be estimated as representing the equivalent of approximately 14 000 average Swedish inhabitants’

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emissions of CO$_2$. This can be compared with the carbon emissions of less than 200 people who live permanently in the catchment, although this comparison disregards substantial emissions from the non-Swedish tourism and transportation activities.

**Keywords:** carbon budgets; greenhouse gas emissions; catchment studies; carbon dioxide; methane

### 1. Introduction

In recent studies of the carbon cycle in natural ecosystems, particular emphasis has been on measuring land–atmosphere exchanges of CO$_2$ and CH$_4$. These measurements give an indication of the short-term net ecosystem exchange (NEE) of carbon between any given ecosystem and the atmosphere which, due to loss as dissolved organic carbon in stream water and off-site removal of organic material in many cases, is different from the longer-term accumulation of carbon in a given ecosystem. Typically, micrometeorological techniques are used for monitoring NEE (Aubinet *et al.* 2000) and are now employed in many biomes of the world. These measurements tend to focus on CO$_2$ fluxes, which are often the major component of carbon exchanges in ecosystems. However, there are ecosystems, where other C-carrying gases such as CH$_4$ comprise a significant component of the total carbon balance. Lateral transport of dissolved organic (DOC), particulate (POC) and inorganic carbon (DIC) in surface and groundwater, and sedimentation in lakes are also the factors that are important for carbon budgeting in heterogeneous landscapes and catchments.

Subarctic ecosystems in the northwestern Atlantic region whose characteristics are often determined by the presence or absence of annually frozen soils (permafrost) are coincident with mean annual temperatures around 0°C. The definition of permafrost requires ground temperatures below 0°C for at least 2 consecutive years in a row (Williams & Smith 1989). Consequently, these environments are particularly sensitive to climate variability (Callaghan *et al.* 2004; Johansson *et al.* 2006a,b). They are, at the same time, often host to substantial amounts of soil organic carbon in the form of peat and other organic soils. Almost one-third of the world’s soil carbon, of the order of 300–400 Gt C (Gorham 1991; Smith *et al.* 2004), is estimated to be stored in boreal and subarctic regions and a large proportion of this carbon has been classified as sensitive to atmospheric release in a changing climate (Tarnocai 2006). However, potential feedbacks between the high latitude carbon loss and the radiative characteristics of the atmosphere have not yet been fully considered in coupled carbon cycle–climate models (but see Sitch *et al.* 2007). There are indications, though, that feedbacks relating to changes in CO$_2$ exchanges alone may have limited impact compared with the effect of anthropogenic emissions over the next 100 years (Zhuang *et al.* 2006). Changes in CH$_4$ emissions from very potent sources released as a consequence of initial climate warming may, however, possess important capabilities for enhancing climate warming further (Walter *et al.* 2006).

The organic soils are evidence of an atmospheric carbon sink function of these ecosystems in the past and peatlands represent an important archive of long-term variations in carbon (C) accumulation rates and their relationship with climate. The presence of peat also indicates long-term wet and anaerobic soil
conditions often associated with substantial production and emissions of methane (\(\text{CH}_4\)). The source strength of the \(\text{CH}_4\) emission is related not only to climatic conditions but, notably, also to surface hydrology and nutrient status reflected in the plant species composition (e.g. Ström et al. 2003) of a given site.

Future climate change may therefore affect not only the carbon balance in the form of \(\text{CO}_2\) exchanges, but also \(\text{CH}_4\) emissions directly through different temperature and soil moisture regimes and also indirectly through that causing vegetation composition change that in itself can cause changes in emission patterns (Ström & Christensen in press).

Here, we evaluate the information available on all major components of the current carbon cycling in a composite subarctic landscape to arrive at a first catchment-scale carbon budget. The study is conducted in the Torneträsk region of subarctic Sweden centred near Abisko and the target years for the budget are 2000–2005. The specification of this time window is important, as the area is undergoing significant environmental change at the decadal time-scale (e.g. Malmer et al. 2005). This region is suited for this type of study owing to the large numbers of research groups involved in carbon cycling work and a unique amount of background monitoring and climate data being available from the Abisko Scientific Research Station (e.g. Kohler et al. 2006).

2. Study area

The Torneträsk catchment (68°22′ N, 19°03′ E; figure 1) covers approximately 3955 km\(^2\) around Lake Torneträsk. A simplified breakdown of the vegetation composition of the region is shown in figure 1, i.e. glacial and barren alpine vegetation, heath, forest, mires and lakes. The vegetation composition and the quantification of areal coverage are based on the SCMD database (Swedish CORINE land cover), which builds on the classification system within EU project, Co-ordination on Information of the Environment (CORINE; Lantmäteriet 2006). The dominant vegetation types are the dwarf shrub heaths and the forest which are mostly subarctic birch (\(\text{Betula pubescens}\) ssp. \text{czerepanovii}\), and also some areas dominated by pine (\(\text{Pinus sylvestris}\)) in the southeastern part of the catchment. The mires are mostly mixed palsa type underlain, in part, by permafrost and are of a complex nature with drier, elevated ombrotrophic parts intermixed with more nutrient-rich wet areas.

3. Methods and data sources

In a heterogeneous landscape, there are exchanges between soil and vegetation pools across and between most ecosystem types (heath, forest, mires, rivers and lakes) that are operative on different time-scales with differing sensitivities to physical and climatic drivers. Nevertheless, there is a temporal sequence that relates to the lateral transfers of DOC and POC in ground and stream water, as it flows from upland production and accumulation areas through downslope transfers to the eventual storage in lake sediments and loss through the headwaters of the Torne River (figure 2). Superimposed on these transfers are all the atmospheric exchanges that are taking place continuously (figure 2) and episodic exchanges.
4. Atmospheric fluxes

The mean estimates for annual land–atmosphere exchanges are based on various types of flux measurements including manual and automated chamber measurements and eddy covariance tower measurements. Although this region is relatively well studied, there are uncertainties in each of these estimates. The high number of both eddy covariance and chamber studies of CO\textsubscript{2} and CH\textsubscript{4} exchange (Svensson et al. 1999; Öquist & Svensson 2002; Christensen et al. 2004; Johansson et al. 2006b) in the Stordalen mire (10 km southeast of Abisko) is the principal source for the wetland flux estimates. In the birch forest, data are obtained from two eddy covariance towers (Johansson et al. in preparation). The lakes have significant ongoing flux measurement activity using both dissolved profile and eddy covariance techniques, and some annual estimates are also available (Jonsson & Karlsson 2003). The lake studies, however, have focused on surface CO\textsubscript{2} exchange and total C transfers. No data are available from this region on the lake fluxes of CH\textsubscript{4}. From the heath, so far, no annual budgets based on eddy covariance are available but, also here, research groups are working on this and annual flux estimates are expected to be available in the near future (R. Baxter 2006, personal communication).

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Based on the collected published and unpublished data sources, we have assigned a most probable average annual budget number to the different ecosystem types of the catchment (table 1) as an average of the years 2000–2005. There are uncertainties and large interannual excursions around the assigned numbers as shown by the approximated minimum and maximum values in table 1. Another uncertainty relates to the representativeness of the particular study locations for the type of ecosystem they represent in the catchment. There is almost certainly a bias among the study sites towards the lower altitudes of the geographical spread of each vegetation type (figure 1), which may lead to a general overestimation of the carbon turnover.

5. Catchment hydrology and run-off

We take a simple bucket approach at estimating the hydrology of the catchment. We have fixed numbers from the Swedish water authorities (Swedish Meteorological and Hydrological Institute, SMHI) on the run-off in the Torne River. We have back-calculated the average run-off from the terrestrial systems based on the assumption that the lake level is constant (341 m.a.s.l.). Measured DOC concentrations in soil and peat water are available for a range of vegetation types in the region including heath, mire and birch forest.

6. Soil/sediment and vegetation storage

The soil storage rates are poorly known for the forest, heath and upland ecosystems. Judging from eddy covariance measurements combined with DOC export estimates, the current plant growth and carbon storage in the forest is
substantial. In the mires that are well known in terms of fluxes, however, the carbon fluxes appear to be a balance between ombrotrophic elevated parts, which are close to a balanced budget (or may in fact be losing carbon; Malmer & Wallén 2004), and minerotrophic wetter areas, which are a net sink of atmospheric CO$_2$ and are accumulating carbon despite also having losses in the form of CH$_4$ and DOC (Johansson et al. 2006b).

In this study, the lake sediment storage numbers are not measured values but appear as a result of the calculations using the numbers presented in table 1. These terms are a key to validating this rough budget. Nevertheless, the numbers for lake sedimentation we calculate are comparable to the measured values in comparable ecosystems in, for example, Finland and Canada.

### 7. Results

(a) Measured parameters

(i) Atmospheric fluxes

The estimated average atmospheric uptake of $-27$ g C m$^{-2}$ yr$^{-1}$ (throughout this paper negative fluxes denote net atmospheric uptake by ecosystems) and CH$_4$ release of $5$ g C m$^{-2}$ yr$^{-1}$ in the mire (table 1) ecosystems is within a well-documented range based on several years of eddy covariance and chamber measurements (with a documented substantial interannual variation). It is also

Table 1. An approximate carbon budget for the Torneträsk catchment during the years 2000–2005. The atmospheric fluxes of CO$_2$ and CH$_4$ indicate an estimated mean with corresponding minimum and maximum given in brackets. Negative numbers mean atmospheric uptake by the ecosystems, positive loss to the atmosphere. All flux numbers are based on the studies referred to in the text. The primary budget does not include estimated DOC displacement. The secondary budget shows the terrestrial components minus DOC export as well as the sedimentation in lakes. Run-off from the catchment is at the bottom of the table. Note that the sign convention shows an uptake by the ecosystems within the catchment as a negative number. Note that Lake Torneträsk is separated from the ‘other’ smaller lakes as they are assumed to have different average atmospheric fluxes. In general, smaller lakes and ponds have much higher rates of atmospheric exchange.

<table>
<thead>
<tr>
<th>area km$^2$</th>
<th>CO$_2$–C g C m$^{-2}$ yr$^{-1}$</th>
<th>CH$_4$–C g C m$^{-2}$ yr$^{-1}$</th>
<th>atm. balance g C m$^{-2}$ yr$^{-1}$</th>
<th>primary ton C yr$^{-1}$</th>
<th>secondary ton C yr$^{-1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>mire 153</td>
<td>$-27$ ($-50$ to $0$)</td>
<td>5 ($2$ to $10$)</td>
<td>$-22$</td>
<td>$-3357$</td>
<td>$-2213$</td>
</tr>
<tr>
<td>heath 1858</td>
<td>$-3$ ($-5$ to $2$)</td>
<td>$-0.1$ ($-0.2$ to $0$)</td>
<td>$-3$</td>
<td>$-5758$</td>
<td>$-93$</td>
</tr>
<tr>
<td>forest, birch 642</td>
<td>$-50$ ($-150$ to $-20$)</td>
<td>$-0.1$ ($-0.2$ to $0$)</td>
<td>$-50$</td>
<td>$-32168$</td>
<td>$-19294$</td>
</tr>
<tr>
<td>forest, pine 121</td>
<td>$-50$ ($-150$ to $-20$)</td>
<td>$-0.1$ ($-0.2$ to $0$)</td>
<td>$-50$</td>
<td>$-6092$</td>
<td>$-5174$</td>
</tr>
<tr>
<td>lakes, rivers 548</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$-7227$</td>
</tr>
<tr>
<td>Torneträsk 345</td>
<td>1 ($0$ to $2$)</td>
<td>0.5 ($0$ to $1$)</td>
<td>2</td>
<td>518</td>
<td></td>
</tr>
<tr>
<td>other lakes 203</td>
<td>20 ($5$ to $30$)</td>
<td>7 ($0.5$ to $20$)</td>
<td>27</td>
<td>5503</td>
<td></td>
</tr>
<tr>
<td>sparse vegetation 457</td>
<td>$-1$ ($-2$ to $1$)</td>
<td></td>
<td>$-1$</td>
<td>$-457$</td>
<td>0</td>
</tr>
<tr>
<td>glaciers 16</td>
<td>0</td>
<td></td>
<td>0</td>
<td>0</td>
<td>16</td>
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<td></td>
<td>0</td>
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<td>3</td>
</tr>
<tr>
<td>missing 159</td>
<td>0</td>
<td></td>
<td>0</td>
<td>0</td>
<td>159</td>
</tr>
<tr>
<td>total 3956</td>
<td></td>
<td></td>
<td>$-41812$</td>
<td>$-33823$</td>
<td></td>
</tr>
<tr>
<td>run-off 7858</td>
<td></td>
<td></td>
<td>19%</td>
<td></td>
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</tr>
</tbody>
</table>

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in the range of long-term peat accumulation studies showing rates in the range of 20 g C m$^{-2}$ yr$^{-1}$ (Malmer & Wallén 2004). It may, however, represent an overestimation of the uptake, in that the eddy correlation measurements have a bias in the fetch towards the wetter part of the mires (Johansson et al. 2006b). This is constrained by the chamber measurements which have a better sub-habitat distribution.

The average uptake of the heath ecosystems, $-3$ g C m$^{-2}$ yr$^{-1}$, is a qualified estimate based on the experimental studies of carbon dynamics and some wintertime measurements showing significant losses of CO$_2$ from these ecosystems during winter (Grogan et al. 2001; Grogan & Jonasson 2006).

The substantial uptake of the birch forest ($-50$ g C m$^{-2}$ yr$^{-1}$) is important for the overall budget. Even higher uptake rates (up to $-150$ g C m$^{-2}$ yr$^{-1}$) than we use in this budget are reported by Johansson et al. (in preparation) and the latter are supported by the measurements in the comparable Finnish mountain birch forests (Aurela et al. 2001). The wintertime measurements available are particularly uncertain (Johansson et al. in preparation); therefore, in this budget, we use a conservative but still substantial estimate for C uptake of $-50$ g C m$^{-2}$ yr$^{-1}$.

No data are available from high northern pine forests in Sweden in terms of annual atmospheric C fluxes. Preliminary data (Aurela 2005) from a comparable site in northern Finland are showing as high a growing season uptake ($-125$ g C m$^{-2}$ per season average 2001–2004) as we measured for the birch forest. Therefore, we also assume a fairly substantial uptake in this forest type of $-50$ g C m$^{-2}$ yr$^{-1}$.

The atmospheric fluxes are largely unknown for the large Lake Torneträsk but better known for smaller lakes. In terms of CO$_2$, substantial atmospheric emissions up to 21 g C m$^{-2}$ yr$^{-1}$ have been measured in some smaller lakes and this excludes the episodic emissions that, most probably, are happening in connection with ice break-up (A. Jonsson 2006, personal communication; Jonsson & Karlsson 2003). Other lakes in the area show similar CO$_2$ fluxes (Jonsson & Karlsson 2003), which are also comparable with the eddy correlation measurements of arctic lake fluxes reported from northern Alaska (Eugster et al. 2003). Lakes in boreal Sweden show even higher surface emissions on a per-square-metre basis (Algesten et al. 2003). Here, we have estimated an average loss of 1 g C m$^{-2}$ yr$^{-1}$ for the large and deep Lake Torneträsk and, based on the studies mentioned previously, a surface emission of 20 g C m$^{-2}$ yr$^{-1}$ for the other smaller lakes.

The atmospheric fluxes of CH$_4$ from lakes have not yet been studied in the region. However, subarctic and arctic lake systems in Alaska as well as Siberia have recently been shown to host substantial CH$_4$ emissions of up to 130 g CH$_4$ C m$^{-2}$ yr$^{-1}$ (Walter et al. 2006). These Siberian lakes are not immediately comparable to the lakes of the Torneträsk catchment due to their different glacial history, but a broad lake survey reported by Bastviken et al. (2004), including comparable Swedish lakes, estimated a range of emissions between 0.5 and 20 g C m$^{-2}$ yr$^{-1}$ as CH$_4$. The emission estimates assigned to lakes here are differentiated between small and large lakes and taken as conservative estimates based on the studies in comparable sites in Sweden and North America (table 1; Bastviken et al. 2004; Walter et al. 2006).
The remaining categories (glaciers and sparse alpine vegetation) are assumed to have negligible atmospheric fluxes (anthropogenic emissions in the urban category are not included in this study).

(ii) Outflow and DOC

The outflow of Torneträsk is fixed at $2.07 \times 10^{12} \, \text{lyr}^{-1}$ which is an average of 20 years of monitoring by the Swedish water authorities (SMHI; T. Jutman 2006, personal communication). The DOC concentration of this water is estimated at an average 3.8 mg C l$^{-1}$, which is from the headwaters and may be a slight overestimation due to increasing forest input to the Torne River as it moves downstream (J. Karlsson 2006, personal communication). The DOC concentrations in the heath and mires are fairly well constrained and between 5 and 15 C mg l$^{-1}$ (Olsrud & Christensen 2004). The important parameter of DOC in birch forest water is an adjusted parameter (mentioned later).

The area estimates of the individual ecosystem types and lake surfaces also represent fixed parameters.

(b) Adjusted and calculated parameters

The overall average run-off minus evaporation term is calculated as $522 \, \text{lm}^{-2} \text{yr}^{-1}$ based on the total run-off from the lake and the size of the catchment. This indicates that the average precipitation of the catchment is significantly higher than the long-term mean (1913–2005) of 306 ml yr$^{-1}$ measured at the Abisko Scientific Research Station. Although the recent precipitation record shows increases in Abisko (360–412 ml yr$^{-1}$ during 2003–2005), the run-off terms from 500 to 1000 l m$^{-2}$ yr$^{-1}$ (across all ecosystems from mires to barren land) are still on average significantly higher than what would be expected from precipitation in Abisko alone. Abisko is, however, well known as the driest place in the region and it is not unreasonable to include these higher numbers in this calculation in order to sustain the measured flow out the Torne River.

The DOC concentration is poorly known in the birch forest systems. There are indications that due to the substantial fresh litter input from this deciduous vegetation type, the DOC concentrations may vary much more seasonally with occasionally very high concentrations during high water flows in the spring and autumn compared with what one could expect from the other ecosystems in the catchment. Sustained extremely high DOC of up to 80 mg C l$^{-1}$ in streams running into small lakes dominated by birch forest surrounding in the area has been observed (A. Jonsson 2006, personal communication). We speculate that very large export terms may be associated with the birch forests in connection with the breakdown of fresh litter and estimate an average DOC content of birch forest soil water at 40 mg C l$^{-1}$.

The end result of this calculation is shown in table 1 and a greenhouse forcing illustration of the atmospheric exchanges is shown in figure 3. Using a general conversion factor (GWP = 23) of CH$_4$ exchanges to produce a landscape-scale greenhouse forcing picture, the CO$_2$ equivalents bars are shown in figure 3. The estimates are corrected for the relative areal coverage of the different vegetation types in the study window (figure 1).

The overall calculation in table 1 shows both a primary budget without considering the DOC transport and a secondary one where the somewhat
speculative DOC transport and displacement terms are incorporated. The average long-term accumulation in the lakes is a result of the calculations and is constrained by the budget, and the resulting number for this is $13 \text{ g C m}^{-2} \text{ yr}^{-1}$. This is within the range of preliminary results from data documenting the sedimentation rates over the past 30 years in a lake in the Stordalen complex showing rates of $7–20 \text{ g C m}^{-2} \text{ yr}^{-1}$ (U. Kokfelt et al. unpublished data). It is also comparable to a range of rates ($7–66 \text{ g C m}^{-2} \text{ yr}^{-1}$) reported from the Finnish lakes (Pajunen 2000) and a mean accumulation rate of $16 \text{ g C m}^{-2} \text{ yr}^{-1}$ reported earlier for an average of 24 lakes across Canada (Boville et al. 1983).

8. Discussion

The budget presented does hold despite the substantial uncertainty in the numbers presented, from gaps in both available measurements and variability within the existing measurements themselves. This exercise is meant to be a first attempt to start discussions and try identifying foci for future research rather than being a final answer.

Uncertainties include the SCMD database (Lantmäteriet 2006), which does not capture the details of the complexities in the catchment landscape. For example, the internal complexity, which is known and has been documented for the palsal mire ecosystems (e.g. Malmer et al. 2005), is not at all captured by...
the spatial scale of the database. This sub-habitat complexity is reflected in the Stordalen mire. This is only one category and we have to assign one flux number, where it is known that it has many different internal facets with respect to the fluxes. Hence, the one number assigned to the mire category has to be balanced correctly against the peatland diversity. We are certain that we do not have the additive balance of the differing and unique plant community structures for all mires correctly. A similar type of uncertainty also applies to other ecosystems, although the palsa mires are exceptionally complex and mixed ecosystems.

There is also an issue of temporal length of the growing season that varies with altitude in an alpine setting. This issue is ignored with the average flux numbers that are estimated for the individual ecosystem types. The issue of complex differences in the temporal lags and lengths of different process drivers is a particular challenge in improving our future models and budgets.

The flux measurements that form the basis for most of this exercise have inherent uncertainties that occur and act over a broad range of temporal and spatial variability. For example, on the seasonal scale, the unresolved issues of wintertime fluxes discussed by Johansson et al. (in preparation) have implications for our overall estimates of the Torneträsk catchment carbon budget. On an episodic scale, using a real event as an analogy for the range of possibilities, this uncertainty can be exemplified by calculations, indicating that insect defoliation of the birch forest which reduce its sink strength by 50% in the forest and 25% on the heath would lead to an overall impact at a large scale by reducing the catchment sink capacity by more than 50%. This means that given the very few measurements available, if one instrument in a birch or a heath ecosystem gives a 50% incorrect estimate, the error will propagate through the budget and become highly significant for the overall result.

The large atmospheric uptake of CO₂ quoted for the forests (table 1) is difficult to reconcile with general plant ecological knowledge, if there is not a substantial loss of DOC, and/or the ecosystems in question are still in an active phase of growth. In the long term, if none of the mentioned components were present, the measured atmospheric uptake would result in very significant build-up of organic matter in the soil and there is no indication of this, currently happening in the forests in question. However, the birch forest in the area may still be expanding above and below the ground biomass following dieback caused by severe insect outbreaks in the 1950s. The measurements presented by Johansson et al. (in preparation) clearly show the massive effect that the insect outbreaks may have on carbon fluxes and it is probable that substantial diebacks caused by such outbreaks could have consequences for C cycling several decades following the events (Tenow & Bylund 2000). Therefore, one part of the explanation for the significant forest uptake is thought to be a real growth of the birch forest. Another part is that DOC export, poorly known as it is, is assumed to be a very significant factor in the carbon budget of the birch forest, in particular, where substantial amounts of labile organic material are made available for decomposition and export following the annual leaf fall.

The overall carbon sink functioning of this subarctic landscape is significant compared with other northern landscape-scale extrapolations. It represents the equivalent of 14 000 average Swedish per capita emission of CO₂ (6 ton CO₂
per capita; Marland et al. 2006) in a landscape that only hosts about 200 permanent citizens (but a lot of tourism and transport activities). Soegaard et al. (2000) used Landsat imagery and elaborate ground-based flux measurements to estimate a relatively small landscape-scale carbon uptake in the range of 2–8 C m$^{-2}$ yr$^{-1}$ for a high arctic valley in northeast Greenland. Comparable estimates for northern Alaskan tundra have varied between source and sink functioning, emphasizing the general variability and climatic sensitivity of the carbon fluxes (Oechel et al. 1993, 2000; Kwon et al. 2006). In a study of the European tundra in Russia, Heikkinen et al. (2004) estimated a net loss of carbon from this ecosystem much of which was associated with thermokarst erosion. Other studies have estimated eastern Siberian tundra as remaining carbon sink (Corradi et al. 2005). Thermokarst erosion lakes in Siberia have occasionally extremely high CH$_4$ emissions (Walter et al. 2006), which point to the importance of the landscape composition and the relative mire and potential lake area for the overall changing climate impact. Many northern landscapes in, for example, Alaska (Reeburgh et al. 1998), Canada (Roulet et al. 1994) and central Siberia (Friborg et al. 2003) have been shown to be sensitive to the emissions of CH$_4$ in their landscape-scale budgets to a varying degree. Compared with the other studies, the Torneträsk catchment is unusually complex and the mires represent a relatively minor component of the landscape as a whole. Hence, the mire emissions and sensitivities in relation to CH$_4$ fluxes and their impact on the overall radiative forcing budget are limited. However, the potential to change a budget from altered CH$_4$ emissions is clearly there and, in particular, the lake emissions represent important understudied wild cards in this budget.

If we apply a doubling of the CH$_4$ emissions from the mires to the budget, the result is a reduction of 20% in the overall CO$_2$ equivalent sink strength. The lake emission of CH$_4$ is also, as mentioned, a potential substantial player in the landscape budget and how it may change in the future. The study region has already seen substantial effects of permafrost thawing (Christensen et al. 2004; Johansson et al. 2006a,b), and if the thaw lake formation in its CH$_4$ emissions is anywhere near what has been documented for other northern lakes (Bastviken et al. 2004; Walter et al. 2006), these emissions may be very important components in the alteration of future greenhouse gas (GHG) budgets from a subarctic landscape such as the one presented here.

Disregarding possible methodological uncertainties, the dominance of the birch forest CO$_2$ uptake rates in this budget also clearly points to the additional sensitivity of the catchment carbon balance to the disturbance of this ecosystem type. As mentioned previously, such a disturbance recently took place in the form of a massive outbreak in 2004 of the autumn moth (Epirrita autumnata) that affected most of the southern part of the birch forest. This reduced the birch forest sink term to a mere zero (Johansson et al. in preparation). If we add such an effect to the current budget and reduce the birch forest atmospheric flux to be in balance with the atmosphere, we reduce the C sink capacity of the catchment by almost 90%.

The total estimated sink capacity of the current catchment is 23 107 tons CO$_2$-C yr$^{-1}$. With a Swedish average per capita emission of 6 tons CO$_2$ yr$^{-1}$ (Marland & Boden 2006) this corresponds to more than 14 000 average citizens emission. This may be compared with the population of less than 200 permanent residents in the catchment.
9. Conclusion

— The Torneträsk region provides a unique opportunity for establishing a reliable catchment-scale carbon budget for a complex subarctic environment.
— We have found that the birch forest carbon balance is crucial for budgeting on the landscape scale, and our preliminary findings indicate that we need to verify the forest storage and dissolved export terms.
— We also know that the mires and lakes are important for the GHG balance, and that they have an important opposite amplifying effect, when the radiative impacts on the climate of CO$_2$ and CH$_4$ exchanges are calculated.
— Large uncertainties are associated with, and important further studies should focus on, the role of DOC exports as a link between the understanding of terrestrial and limnological data on landscape-scale CO$_2$ and CH$_4$ fluxes.

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