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Integrating carbon emissions from lakes and streams in a subarctic catchment

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Northern inland waters emit CO₂ and CH₄ to the atmosphere but the importance of these emissions is poorly understood due to a lack of integrated catchment-scale estimates of carbon (C) emissions from lakes and streams. In this study we quantified the annual emission of CO₂ and CH₄ from 27 lakes and 23 stream segments in a 15 km² subarctic catchment in northern Sweden. All lakes and streams were net sources of C to the atmosphere on an annual basis. Streams dominated (96%) the aquatic CO₂ emission while lakes (61%) dominated the aquatic CH₄ emission. Total aquatic C emission from the catchment was estimated to be 9.1 g C m⁻² yr⁻¹ (98% as CO₂). Although streams only accounted for 4% of the aquatic area in the catchment, they accounted for 95% of the total emission. The C emissions from lakes and streams were considerably larger than previously reported downstream waterborne export of C from the catchment, indicating that the atmospheric losses of C in the aquatic systems are an important component in the catchment C balance.


1. Introduction

A thorough understanding of global carbon (C) cycling is a key issue in order to accurately predict future global climate and related impacts on ecosystems [Intergovernmental Panel on Climate Change, 2007]. High-latitude boreal, subarctic, and arctic regions are recognized as areas of special interest in a future warming climate, as the surface air temperature increase is predicted to be amplified toward northern high latitudes [Serreze and Francis, 2006]. High-latitude ecosystems are also sensitive to changing climate [Roots, 1989] and may in turn feedback on the climate system, e.g., by mobilization and release of C stored in permafrost [Schuur et al., 2009]. Efforts are currently invested in understanding land-atmosphere C exchange at high latitudes and its response and feedback effects to climate variables. However, these efforts are mainly focused on terrestrial systems and do normally not consider the lateral loss and fate of terrestrial C in aquatic systems [Christensen et al., 2012; Houghton, 2003; Sarmiento et al., 2010].

Inland waters have recently been identified not only as a transport medium of inorganic and organic C but also as an active component in the global C cycle by both storing and emitting C during its passage from land to sea [Aufdenkampe et al., 2011; Butman and Raymond, 2011; Dinsmore et al., 2010; Humborg et al., 2010; Tranvik et al., 2009]. Global estimates suggest that more than half of the terrestrial C export is lost in inland waters and mainly so as gas evasion to the atmosphere [Aufdenkampe et al., 2011; Tranvik et al., 2009]. This atmospheric loss is direct via evasion of CO₂ and CH₄ imported in supersaturated soil water [Hope et al., 2004; Kling et al., 1991; Walter et al., 2007] or indirect after mineralization of terrestrial organic C by biological and photochemical processes inside the aquatic systems [Bertilsson and Tranvik, 2000; Karlsson, 2007]. For the CH₄ emission, an important source is also internal decomposition of autochthonous organic C in lake sediments [Kelly and Chynoweth, 1981; Walter et al., 2008]. Northern lakes and streams are generally net sources of C to the atmosphere [Bartlett et al., 1992; Giesler et al., 2013; Jonsson et al., 2003; Laurion et al., 2010; Striegl et al., 2012; Teodoru et al., 2009]. Irrespective of the relative importance of the pathways leading to C emission from inland waters, these losses must be accounted for and integrated with terrestrial C fluxes for a complete land-atmosphere C exchange estimate [Battin et al., 2009].

The quantitative importance of high-latitude aquatic systems in the release of C to the atmosphere remains unclear, largely due to a lack of studies integrating CO₂ and CH₄ fluxes for complete aquatic networks at a relevant time scale. The few studies on land-atmosphere C exchange that have been carried out for high-latitude catchments all identify aquatic systems as significant sources of atmospheric...
None of them, however, include atmospheric C exchange with first-order streams. Recent research in boreal catchments show high CO₂ concentrations and gas transfer velocities in streams versus lakes, resulting in significant emission from streams despite only covering a small portion of the aquatic area of the regions studied [Koprivnjak et al., 2010; Teodoru et al., 2009]. Concerning CH₄ emissions from lakes and streams, it could be assumed that lakes are generally of larger importance due to favorable conditions for CH₄ production in lake sediments and that this production is high compared to the sum of external input and internal production in streams, but it is also possible that such differences are counteracted by relatively higher CH₄ oxidation in the water column of lakes versus streams [Bastviken et al., 2004].

The lack of integrated estimates of emissions of CO₂ and CH₄ from lakes and streams precludes a deeper understanding of the relevant properties of the aquatic network necessary for accurate upscaling, and assessment of the large-scale role of inland waters for land-atmosphere C exchange. The aim of this study was to assess the relative importance of lakes and streams in the annual emission of CO₂ and CH₄ from a high-latitude catchment. We sampled all aquatic systems (27 lakes and 23 stream segments) in a 15 km² subarctic catchment during 1 year, estimated the integrated aquatic C emission for the whole catchment, and compared this estimate to published C export from the catchment.

2. Methods

2.1. Site Description

The study was carried out in 2009 in the Stordalen catchment (15 km², 68°N, 19°E) in subarctic Sweden (Figure 1). Mean annual air temperature for 2000–2009 was 0.6 ± 0.4°C, and the coldest and warmest months were February (−9.5 ± 3.1°C) and July (12.5 ± 1.2°C), respectively. The average annual total precipitation for the same period was 340 ± 56 mm, of which about 40% occurs between November and May when the lakes in the catchment generally are ice covered. All climatological data were recorded at Abisko Scientific Research Station (http://www.polar.se/abisko), located 10 km from the studied catchment. The catchment includes alpine terrain dominated by heaths and dwarf shrubs (e.g., Empetrum hermaphroditum, Vaccinium sp., and Betula nana) at high altitudes (600–770 m above sea level (asl)) and subalpine terrain covered with mountain birch forest (Betula pubescens ssp. czerepanovii) and mires dominated by Sphagnum mosses at low altitudes (360–600 m asl). The mires contain patches of permafrost and areas of palsa and the active layer is approximately 60 cm [Johansson et al., 2006; Malmer et al., 2005]. The catchment contains 27 lakes (0.001–0.145 km²), of which one is alpine and the others are subalpine and surrounded by mire and birch forest. Most of the lakes are connected by a network of streams. The streams all start as small (< 1 m wide, < 0.5 m deep) streams in the part of the catchment where it is relatively steep, but subsequently flow through...
flatter mires where they grow deeper, wider, and less turbulent. The catchment pour point is through the outlet of lake L1 (Figure 1).

2.2. Sampling

[7] Twenty-six of the lakes in the catchment were sampled monthly during the ice-free season from mid-May to the end of September. The high alpine lake was sampled twice from mid-July to early September. Samples for CO2, dissolved organic C (DOC), dissolved inorganic C (DIC), CH4, and pH were taken at the deepest part of the lake at a depth of 1 m. For seven of these lakes, CO2 and CH4 were also sampled while being ice covered in April [Karlsson et al., 2013]. The catchment stream network was grab sampled biweekly for CO2 and monthly for DOC, DIC, CH4, and pH at 23 different locations from the beginning of May to mid-October. We, however, continued the sampling program in those streams not being ice covered after mid-October. The locations were chosen so that each stream location represented a segment (50 to 2000 m long) with uniform morphology flowing through homogenous soil and vegetation types. At the lower elevation of the catchment, sampling locations were also chosen in stream sections connecting lakes and in some cases after stream confluences.

[8] Water samples for CO2 analyses were sampled in triplicate using 60 mL plastic syringes with plastic valves (Becton Dickinson Plastipak, U.S.). A 1 L acid-washed polyethylene bottle was used to collect samples for DOC analysis, and a 100 mL gastight acid-washed glass bottle (Schott Duran, Germany) was used to collect samples for DIC, CH4, and pH analyses. All bottles and syringes were rinsed with stream or lake water before use. The samples were transported back to the laboratory and kept in a refrigerator until they were processed. Water temperature was measured in situ with a multiprobe (340i; WTW GmbH, Germany) at the same depth as the water sample was taken. Wind data were collected with a sonic anemometer (R3, Gill Ltd., UK), located on a stationary raft in lake L1 at a height of 1.65 m over the water surface, and were assumed to be representative of the whole catchment. Wind speed was measured continuously and logged as 30 min averages. Air CO2 concentrations were obtained from in situ air measurements with an infrared gas analyzer (Li-820, Li-COR, U.S.) and a logger (CR10X, Campbell Inc., U.S.) located on the raft in lake L1. Air CO2 concentrations were measured and logged every 7 h.

2.3. Chemical Analyses

[9] All samples were processed on the day of sampling. The CO2 concentration of the water was measured with a headspace equilibrium technique [Cole et al., 1994; Karlsson et al., 2010]. Thirty milliliters of water was discarded and replaced by 30 mL of reference air in each syringe and shaken for 1 min, followed by 1 min of equilibration between the gas and liquid phases. The pCO2 in the headspace and reference air were analyzed using an infrared gas analyzer (EGM 3 and EGM 4, PP Systems Inc., U.S.). Measured values were linearly calibrated against CO2 standard gases (365, 2000, and 5010 ppm, R2 > 0.99, mean of coefficients of variation (CV)=2.8%). The water concentration of CO2 was calculated from the mean headspace pCO2, normalized to the reference air sample, by using Henry’s law, given the temperature dependency of Henry’s constant, the temperature of the solution, and the volume relationship between liquid and gas phases [Aberg et al., 2007]. DOC was analyzed after filtration (0.45 μm sterile filter, Filtrupor S, Sarstedt AG & Co., Germany) and acidification (100 μL 20% HCl to 50 mL filtrate) by high-temperature catalytic oxidation using a Shimadzu TOC-V CPH analyzer (Shimadzu Corporation, Japan, CV=5.5%). DIC and CH4 concentrations were determined in the headspace after addition of 20 μL 20% HCl to 4 mL water in a gastight vial (22 mL vials, PerkinElmer Inc., U.S.) using a gas chromatograph (Clarus 500, PerkinElmer Inc., U.S.), equipped with a methanizer and a flame ionization detector. Internal standards for DIC and CH4 were prepared, stored, and analyzed together with each batch of samples (R2 > 0.99). Water pH was measured in the lab with a pH electrode (MP220, Mettler Toledo International Inc.).

2.4. GIS Analyses

[10] Areas of lakes and streams were obtained by digitizing an orthophoto (1 m pixel resolution) using the software package ArcGIS 9.3.1 (ESRI, U.S.). It was not possible to estimate the area of stream segments with a width smaller than approximately 1.5 m by remote sensing, due to a combination of too low image resolution and too dense surrounding vegetation. These stream segments were instead assumed to be uniform channels with a width (w) estimated from field measurements at each sample location. The average depth (z), representing the segment of the streams, was estimated in the field at each sample location. Slope gradient calculations were obtained by a rise over run calculation for all stream segments. The elevation values and length calculations were conducted using a high-resolution lidar-derived digital elevation model (DEM) with a 1 m resolution. The elevation accuracy in the DEM is 0.03 m due to high-density sampling and low flying altitude [Hasan et al., 2012]. The catchment area was modeled in a 10 m resolution DEM with the hydrology tools available in ArcGIS 9.3.1. Volumes of the seven lakes sampled in winter were determined from interpolations of integrated GPS and echo-sounding depth measurements (m52i, Lowrance, U.S.). The interpolations were based on, in total, 3477 depth measurements, from 122 in the smallest lake to 1370 in the biggest lake. The interpolations were performed in the ArcGIS 9.3.1 geostatistical analysis package using the ordinary kriging method. Maximum depths were confirmed by manual depth measurements.

2.5. Flux Estimations

[11] We estimated the diffusive fluxes between water surface and atmosphere for each stream segment and lake by using Fick’s law after Jonsson et al. [2008] and corrected for the chemical enhancement factor (α, for CO2 only), calculated as a function of pH, due to alkaline conditions [Kuss and Schneider, 2004; Wanninkhof and Knox, 1996]:

\[
\text{Flux} = \alpha k_i (C_{\text{water}} - C_{\text{eq}})
\]

where \( k_i \) (cm h\(^{-1}\)) is the gas-specific transfer velocity at the measured temperature, \( C_{\text{water}} \) is the gas concentration in water, and \( C_{\text{eq}} \) is the air-water equilibrium concentration, which was calculated from air pCO2 measurements above
the gas transfer velocity at a certain temperature with a CO₂ re-aeration coefficient (K_CO₂) and stream segment slope (in %), w and z, as estimated by Wallin et al. [2011] from propane (C₃H₈) injection experiments in small boreal first-order streams:

\[ k_600 = K_{CO_2} \times z \]  

Lake fluxes were determined from a wind-dependent k_600 function, developed from a SF₆ addition experiment in a small (0.15 km²) temperate lake [Cole and Caraco, 1998]:

\[ k_{600} = 2.07 + 0.215U_{10}^{-1.7} \]  

where \( U_{10} \) is the wind speed at a height of 10 m (monthly averages). The \( U_{10} \) was calculated from measured wind speed \( U_z \) [Crusius and Wanninkhof, 2003]:

\[ U_{10} = U_z \left\{ 1 + \left[ \left( \frac{C_{d10}}{k} \right)^{1/2} / k \right] \ln(10/z) \right\} \]  

where \( C_{d10} \) is the drag coefficient at 10 m height (0.0013) [Large and Pond, 1981], \( k \) is von Karman’s constant (0.41) [Vachon et al., 2010], and \( z \) is the height of the anemometer.

[12] Ice-free-season gas emission was calculated as the product of fluxes and lake area integrated over time. Lake ice-free season was integrated from the day the first open water sample in each lake was taken (around 1 week after ice breakup) to when all lakes were ice covered in the beginning of October, which gives an estimated ice-free season between 130 and 135 days for lakes at lower elevation and 86 days for the alpine lake. Emission of CO₂ and CH₄ at ice breakup in the seven sampled lakes was determined as the difference in the amount of CO₂ and CH₄ between the sampling occasion under spring ice and the first open water sampling after ice breakup [Karlsson et al., 2013]. Only lakes with a maximum depth above 1.5 m were assumed to accumulate gases during the winter season since shallower lakes freeze solid during winters. We extrapolated the results from the seven lakes sampled in winter to the other lakes in the catchment with a maximum depth above 1.5 m, from the mean ratio of the ice breakup emissions to June emissions (the first month after ice breakup). Due to the lack of CH₄ data for one lake, we assumed that the relationship between CO₂ and CH₄ emissions was the same as in the most nearby lake of the same size.

[13] The emissions were calculated for each of the 23 stream segments as the product of fluxes and area of each segment integrated over time. Total C emission from the stream network was calculated as the sum of emissions from all segments. The streams were ice free from approximately 1 May and were estimated to freeze between 15 October and 1 December, depending on location. We did not include any enhanced flux at stream ice breakup due to outgassing of accumulated CO₂ and CH₄ under ice, since a clear majority of the streams in Stordalen are frozen solid during the end of the winter [Karlsson et al., 2013].

### 2.6. Statistics and Error Estimates

[14] The gas concentration data were normally distributed in streams but not in lakes. Therefore, we used the Mann-Whitney U test for statistical comparisons between lake and stream CO₂ and CH₄ concentrations. Concentration and fluxes are always reported as the mean of lakes and streams (±1 standard deviation). Due to the use of median values in the function calculating stream \( K_{CO_2} \) by Wallin et al. [2011], we also present stream fluxes as median values (± the median absolute deviation). The relative standard deviation in the emission estimates (RSD_emission), which is defined as the ratio of the standard deviation against the value, was calculated due to common rules of error propagation in multiplication of parameters:

\[ RSD_{emission} = \sqrt{RSD_{x-z}^2 + RSD_x^2 + RSD_z^2} \]  

where \( RSD_{x-z} \) is the relative standard deviation of each parameter being a source of random errors. We included the random errors introduced by sampling and analytical procedures of CO₂ and CH₄ concentrations in all systems. For stream emissions, we also included the uncertainty in stream area and depth estimates and what is introduced by the gas transfer coefficients function [see Wallin et al., 2011]. Lake emissions errors estimates also included uncertainties in the wind speed measurements and the uncertainty introduced when upscaling ice breakup emissions.

### Table 1. Physical and Chemical Characteristics of Lakes in the Stordalen Catchment During the Ice-Free Season 2009

<table>
<thead>
<tr>
<th>Lakes</th>
<th>Area</th>
<th>Max Depth</th>
<th>Temperature</th>
<th>DOC</th>
<th>DIC</th>
<th>pCO₂</th>
<th>pCH₄</th>
</tr>
</thead>
<tbody>
<tr>
<td>(n=27)</td>
<td>(km²)</td>
<td>(m)</td>
<td>(°C)</td>
<td>(mg L⁻¹)</td>
<td>(mg L⁻¹)</td>
<td>(μatm)</td>
<td>(μatm)</td>
</tr>
<tr>
<td>Mean</td>
<td>0.026</td>
<td>2.8</td>
<td>11.5</td>
<td>10</td>
<td>5.2</td>
<td>720</td>
<td>580</td>
</tr>
<tr>
<td>Max</td>
<td>0.145</td>
<td>8.5</td>
<td>14.5</td>
<td>22</td>
<td>18.4</td>
<td>2870</td>
<td>2980</td>
</tr>
<tr>
<td>Min</td>
<td>0.001</td>
<td>0.5</td>
<td>7.4</td>
<td>7</td>
<td>2.5</td>
<td>310</td>
<td>150</td>
</tr>
<tr>
<td>1 SD</td>
<td>0.039</td>
<td>2.1</td>
<td>2.0</td>
<td>3</td>
<td>3.0</td>
<td>520</td>
<td>710</td>
</tr>
</tbody>
</table>

### Table 2. Physical and Chemical Characteristics of Streams in the Stordalen Catchment During the Ice-Free Season 2009

<table>
<thead>
<tr>
<th>Streams</th>
<th>Width</th>
<th>Temperature</th>
<th>DOC</th>
<th>DIC</th>
<th>pCO₂</th>
<th>pCH₄</th>
</tr>
</thead>
<tbody>
<tr>
<td>(n=23)</td>
<td>(m)</td>
<td>(°C)</td>
<td>(mg L⁻¹)</td>
<td>(mg L⁻¹)</td>
<td>(μatm)</td>
<td>(μatm)</td>
</tr>
<tr>
<td>Mean</td>
<td>1.5</td>
<td>8.9</td>
<td>10</td>
<td>7.7</td>
<td>3990</td>
<td>880</td>
</tr>
<tr>
<td>Max</td>
<td>6</td>
<td>14.0</td>
<td>17</td>
<td>14.0</td>
<td>10570</td>
<td>2920</td>
</tr>
<tr>
<td>Min</td>
<td>0.5</td>
<td>5.7</td>
<td>5</td>
<td>3.4</td>
<td>460</td>
<td>100</td>
</tr>
<tr>
<td>1 SD</td>
<td>1.4</td>
<td>2.2</td>
<td>3</td>
<td>2.8</td>
<td>2870</td>
<td>670</td>
</tr>
</tbody>
</table>

*Based on field measurements at each sample location.*
3. Results

[15] About 0.74 km² or 5% of the total catchment area is composed of aquatic systems. Lakes dominate, accounting for 0.71 km² or 96% of the total aquatic area, whereas streams account for 0.03 km² or 4% of the total aquatic area. Both lakes and streams were relatively small, the mean lake area being 0.026 km² with a mean maximum depth of 2.8 m (Table 1) and the mean stream width at the sampling locations being about 1.5 m (Table 2). Stream slopes ranged between <1 and approximately 22%, giving an estimated $k_{600}$ range between 9 and 352 cm h\(^{-1}\).

[16] Mean DOC concentration was 10 ± 3 mg L\(^{-1}\) in both lakes and streams while mean DIC concentration was 5.2 ± 3.0 and 7.7 ± 2.8 mg L\(^{-1}\), respectively (Tables 1 and 2). All streams were supersaturated with CO₂ in relation to the atmosphere (mean atmospheric summer concentration: 337 μatm) on all sampling occasions; the overall mean stream $pCO_2$ was 3930 ± 2870 μatm. Streams were also supersaturated with CH₄ (870 ± 660 μatm) except at one site in August (Table 2). During the open water season, lake $pCO_2$ (720 ± 520 μatm), and to lesser extent $pCH_4$ (580 ± 710 μatm), were generally low compared to partial pressures in streams (Mann-Whitney $U$ test $CO_2$: $p < 0.001$, $CH_4$: $p = 0.022$). Lake CO₂ and CH₄ partial pressures were high before ice breakup ($pCO_2$: 13,520 ± 11,240 μatm, $pCH_4$: 124,000 ± 116,780 μatm) compared to the ice-free period.

[17] Average stream CO₂ (mean: 15,600 ± 8000, median: 10,300 ± 5400 mg C m\(^{-2}\) d\(^{-1}\)) and CH₄ (mean: 190 ± 30, median: 100 ± 20 mg C m\(^{-2}\) d\(^{-1}\)) fluxes were higher than lake CO₂ and CH₄ fluxes throughout the ice-free season (Figure 2). Estimated average lake CO₂ and CH₄ flux during the ice-free season was 180 ± 110 and 9 ± 6 mg C m\(^{-2}\) d\(^{-1}\), respectively. Thus, the total C flux (i.e., the sum of CO₂ and CH₄) to the atmosphere was about 2 orders of magnitude higher from streams than from lakes during the ice-free season. Including ice breakup, the average annual flux of CO₂ and CH₄ from lakes was 8 ± 4 and 2 ± 0.9 g C m\(^{-2}\) yr\(^{-1}\), respectively. The spatial distribution of annual C fluxes is displayed in Figure 3, showing high fluxes from streams compared to lakes in all parts of the catchment.

[18] The sum of annual CO₂ and CH₄ emissions per unit of catchment area from lakes and streams (Figure 4) was 9.1 ± 5.4 g C m\(^{-2}\) yr\(^{-1}\), of which 98% was emitted as CO₂. Large stream fluxes compensated for the relatively small stream area, so that streams dominated the aquatic C emission and accounted for 95% (8.6 ± 5.3 g C m\(^{-2}\) yr\(^{-1}\)) of the total aquatic C emission. Of the emission from lakes ($0.51 ± 0.22$ g C m\(^{-2}\) yr\(^{-1}\)), 45% ($0.23 ± 0.08$ g C m\(^{-2}\) yr\(^{-1}\)) was emitted during a short period after ice breakup (Figure 4).
Lakes and streams had different roles in CH$_4$ and CO$_2$ emissions from the catchment with streams dominating the CO$_2$ emission (96% of total) and lakes dominating CH$_4$ emission (62% of total). Uncertainties in data affected the emissions in respective system but did not have any major effect on the main difference between lakes and streams (Figure 4).

4. Discussion

[19] Our study stresses the need to integrate C emissions from lakes and streams in order to obtain accurate catchment-scale estimates of aquatic CO$_2$ and CH$_4$ emissions. Both lakes and streams contributed to the emission of CO$_2$ and CH$_4$ but with large differences across systems, with streams dominating the CO$_2$ emission and lakes dominating the CH$_4$ emission.

[20] Interestingly, small streams dominated the total aquatic C emission in the catchment, even though the streams only covered about 4% of the total aquatic area. Although no studies have compared catchment-scale C emissions from lakes and streams, our data are in general agreement with published estimates of higher C fluxes from streams than from lakes. Our estimated average vertical CO$_2$ flux from streams is an order of magnitude larger than those of Koprivnjak et al. [2010] and Teodoru et al. [2009], but within the range found by Wallin et al. [2011]. The average vertical flux of CH$_4$ from streams was higher than what was estimated for streams on Alaska’s North Slope [Reeburgh et al., 1998]. The flux of CH$_4$ from streams was small compared to the flux of CO$_2$ which is consistent with previous studies on streams in temperate and boreal regions [Hope et al., 2001]. In contrast to streams, there have been many estimates of CO$_2$ and CH$_4$ fluxes from subarctic and arctic lakes. The average diffusive fluxes of CO$_2$ and CH$_4$ from lakes during the ice-free season were comparable to earlier reports from Alaska, Canada, and northern Sweden.
[Jonsson et al., 2003; Kling et al., 1992; Laurion et al., 2010; Reeburgh et al., 1998].

[21] The high C fluxes from streams compared to lakes and to other stream C flux estimates in the literature can be ascribed not only to high gas concentrations but also to high gas transfer velocities. Two recent studies have shown stream slope to be a good predictor of gas exchange velocities [Raymond et al., 2012; Wallin et al., 2011]. Stordalen is a relatively steep catchment compared to the catchments where similar studies have been carried out. Steep, small, and turbulent streams cause high gas transfer velocities, resulting in higher estimated C fluxes than previously reported from northern streams. Since some segments of the streams in our study are steeper than those included in the gas transfer velocity model, we extrapolated gas transfer velocities in the part of the catchment steeper than 6.8% (accounting for 36% of the total stream area and about 40% of the total stream C flux) [Wallin et al., 2011]. Still our estimated gas transfer velocities are in the range of those in Raymond et al. [2012].

[22] For the lakes, we estimated the CO2 and CH4 fluxes by using the wind speed-based model reported by Cole and Caraco. [1998], because this model was developed in relatively small lakes (0.15 km2), comparable to those in the Stordalen catchment. Lake size determines to some extent the wind impact on the lake gas exchange, since a longer fetch results in higher surface turbulence [Jonsson et al., 2008; Wanninkhof, 1992]. Jonsson et al. [2008] developed another gas transfer velocity model based on eddy covariance measurements carried out in a 3.8 km2 subarctic lake. Using that model for gas flux calculations in our catchment would increase the annual flux of C to the atmosphere by around 50% but only slightly increase the importance of lakes in the catchment. Thus, the effect of uncertainties in gas transfer velocities on the total aquatic C flux is likely small in lakes compared to streams. The wind speeds recorded at lake L1 might be higher compared to those in small and more protected lakes, implying that we overestimated vertical C fluxes in smaller lakes. Lake L1 is, however, the single most important lake for C emissions, alone accounting for about 30% of the C emission from lakes, which supports our choice of location for wind measurements. Nevertheless, it is unlikely that uncertainties introduced by spatial wind variations and the wind-based model would change the general picture of small streams as the most important aquatic component for C emission to the atmosphere.

[23] Our study stresses that the relative importance of lakes and streams in aquatic C emissions differs for CO2 and CH4 (Figure 4). Ebulition of CH4 was not included in our study, which could constitute an important part of the CH4 emissions from lakes. Data from six of the lakes included in this study, collected in 2010, show that the contribution of ebullition was between 10% and 90% of total emissions (E. J. Lundin et al. unpublished data, 2010), which further emphasizes the importance of lakes in CH4 emissions. We interpret the contrasting roles of lakes versus streams as reflecting the difference in the major sources of gases between systems, i.e., mainly external input for streams and mainly internal production for lakes. The high emission of CO2 from streams likely results from the input of CO2 supersaturated water from soils [Hope et al., 2004]. For lakes, internal respiration of terrestrial organic C is an important contributor of CO2 [Ask et al., 2012; Karlsson et al., 2010]. Although streams contributed significantly to the CH4 emission, it is clear that lakes are important sites for emission of CH4, which is attributable to organic-rich sediments favoring CH4 production [Kelly and Chynoweth, 1981; Walter et al., 2008]. Irrespective of origin, the C outgassed from aquatic systems represents a loss of C from the catchment to the atmosphere that has to be accounted for in regional C balances.

[24] Emission of C from aquatic systems is an important component of the C balance in subarctic and arctic catchments [Christensen et al., 2007; Karlsson et al., 2010; Kling et al., 1991], and is comparable to the lateral waterborne C export from the catchments. The annual C export from the Stordalen catchment in 2009 was estimated to be 2.8 g C m⁻² yr⁻¹, of which about 0.7 g C m⁻² yr⁻¹ (25%) consisted of DIC, about 2.0 g C m⁻² yr⁻¹ (71%) of DOC, and the remaining 0.1 g C m⁻² yr⁻¹ (4%) of particulate organic C [Olefeldt et al., 2012]. Olefeldt et al. [2012] suggest that the C export represents about 10% to 30% of the catchment net ecosystem exchange (NEE, including fluxes from both terrestrial environments and lakes). Our study shows that the C emission from the aquatic system in Stordalen (9.1 ± 5.4 g C m⁻² yr⁻¹) is considerably larger than the export from the catchment. This implies that the vertical losses of C from the catchment via aquatic systems correspond to a significant proportion of NEE, indicating that an integration of aquatic systems into the land-atmosphere C balance would change catchment NEE significantly compared to an estimate based on terrestrial C fluxes alone. Thus, similar to the findings of Wallin et al. [2013], our results show that aquatic systems in general and small streams in particular, can be an important component of C cycling at the catchment level. This indicates an essential role for inland waters in terrestrial C budgets that, if ignored, would result in overestimation of the landscape C sink.

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