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Integrating carbon emissions from lakes and streams in a subarctic catchment

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[1] 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.

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1. Introduction

[2] 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].

[3] 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].

[4] 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

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Figure 1. The Stordalen catchment. Open symbols indicate the location of the study lakes and closed symbols the streams sampling locations. The theoretical catchment pour point is through the outlet of lake L1. Coordinates are given in decimal degrees (World Geodetic System (WGS) 84).

C [Christensen *et al.*, 2007; Karlsson *et al.*, 2010; Kling *et al.*, 1991]. None of them, however, include atmospheric C exchange with first-order streams. Recent research in boreal catchments show high CO_2 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 CH_4 emissions from lakes and streams, it could be assumed that lakes are generally of larger importance due to favorable conditions for CH_4 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 CH_4 oxidation in the water column of lakes versus streams [Bastviken *et al.*, 2004].

[5] The lack of integrated estimates of emissions of CO_2 and CH_4 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 CO_2 and CH_4 from a high-latitude catchment. We sampled all aquatic systems (27 lakes and 23 stream segments) in a 15 km^2 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

[6] The study was carried out in 2009 in the Stordalen catchment (15 km^2 , 68°N , 19°E) in subarctic Sweden (Figure 1). Mean annual air temperature for 2000–2009 was $0.6 \pm 0.4^\circ\text{C}$, and the coldest and warmest months were February ($-9.5 \pm 3.1^\circ\text{C}$) and July ($12.5 \pm 1.2^\circ\text{C}$), respectively. The average annual total precipitation for the same period was $340 \pm 56 \text{ mm}$, 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 palsas 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 km^2), 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 ($< 1 \text{ m}$ wide, $< 0.5 \text{ m}$ 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, $R^2 > 0.99$, 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 [Åberg *et al.*, 2007]. DOC was analyzed after filtration (0.45 µm sterile filter, Filtropur 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 ($R^2 > 0.99$). 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]:

$$Flux = \alpha k_t (C_{\text{water}} - C_{\text{equ}}) \quad (1)$$

where k_t (cm h⁻¹) is the gas-specific transfer velocity at the measured temperature, C_{water} is the gas concentration in water, and C_{equ} is the air-water equilibrium concentration, which was calculated from air pCO₂ measurements above

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

Lakes (<i>n</i> = 27)	Area (km ²)	Max Depth (m)	Temperature (°C)	DOC (mg L ⁻¹)	DIC (mg L ⁻¹)	<i>p</i> CO ₂ (μatm)	<i>p</i> CH ₄ (μatm)
Mean	0.026	2.8	11.5	10	5.2	720	580
Max	0.145	8.5	14.5	22	18.4	2870	2980
Min	0.001	0.5	7.4	7	2.5	310	150
1 SD	0.039	2.1	2.0	3	3.0	520	710

the surface at lake L1 and from the global atmosphere *p*CH₄ average (1.8 μatm [Dlugokencky *et al.*, 2009]). The *k*₆₀₀ is the gas transfer velocity at a certain temperature with a Schmidt number (*Sc*) of 600. The *k_t* for both CO₂ and CH₄ exchange was therefore calculated from *k*₆₀₀, as done by Jähne *et al.* [1987]:

$$k_t = k_{600}(Sc_t/Sc_{600})^n \quad (2)$$

Sc_t for the measured temperature was calculated as done by Wanninkhof [1992], and the *Sc* exponent *n* was given the value of −0.5 since all water surfaces were assumed to be rippled [Jonsson *et al.*, 2008]. The *k*₆₀₀ were calculated for all 23 stream segments by using the relationship between CO₂ re-aeration coefficients (*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:

$$\text{median } K_{\text{CO}_2} = 0.013 \text{ slope} + 0.002w/z - 0.000003 \quad (3)$$

where *K*_{CO2}, normalized to 20°C, relates to *k*₆₀₀ as [Genereux and Hemond, 1992; Wallin *et al.*, 2011]

$$k_{600} = K_{\text{CO}_2} \times z \quad (4)$$

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]:

$$k_{600} = 2.07 + 0.215U_{10}^{1.7} \quad (5)$$

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]:

$$U_{10} = U_z \left\{ 1 + \left[(C_{d10})^{1/2} / \kappa \right] \ln(10/z) \right\} \quad (6)$$

where *C*_{d10} is the drag coefficient at 10 m height (0.0013) [Large and Pond, 1981], *κ* 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*_{CO2} 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:

$$\text{RSD}_{\text{emission}} = \sqrt{\text{RSD}_x^2 + \text{RSD}_y^2 + \text{RSD}_z^2 \dots} \quad (7)$$

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 uncertainty in the wind speed measurements and the uncertainty introduced when upscaling ice breakup emissions.

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

Streams (<i>n</i> = 23)	Width ^a (m)	Temperature (°C)	DOC (mg L ⁻¹)	DIC (mg L ⁻¹)	<i>p</i> CO ₂ (μatm)	<i>p</i> CH ₄ (μatm)
Mean	1.5	8.9	10	7.7	3,990	880
Max	6	14.0	17	14.0	10,570	2,920
Min	0.5	5.7	5	3.4	460	100
1 SD	1.4	2.2	3	2.8	2,870	670

^aBased on field measurements at each sample location.

Figure 2. Spatial mean vertical flux (± 1 standard deviation) of (a) CH₄ and (b) CO₂ from lakes and streams during the ice-free season in the Stordalen catchment. No mean stream CH₄ flux is shown for October since the majority of streams was frozen before the sampling occasion. Note logarithmic scale.

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 μ atm) on all sampling occasions; the overall mean stream p CO₂ was 3930 ± 2870 μ atm. Streams were also supersaturated with CH₄ (870 ± 660 μ atm) except at one site in August (Table 2). During the open water season, lake p CO₂ (720 ± 520 μ atm), and to lesser extent p CH₄ (580 ± 710 μ atm), were generally low compared to partial pressures in streams (Mann-Whitney U test CO₂: $p < 0.001$, CH₄: $p = 0.022$). Lake CO₂ and CH₄ partial pressures were

high before ice breakup (p CO₂: $13,520 \pm 11,240$ μ atm, p CH₄: $124,000 \pm 116,780$ μ atm) compared to the ice-free period.

[17] Average stream CO₂ (mean: $15,600 \pm 8000$, median: $10,300 \pm 5400$ 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).

Figure 3. Spatial distributions of the annual C fluxes calculated for each component in the catchment. The white line shows the border of the catchment. Coordinates are given in decimal degrees (WGS 84).

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

Figure 4. Calculated annual C emissions per catchment area unit of CO_2 and CH_4 from lakes and streams in the Stordalen catchment. Error bars express the uncertainty (standard deviation) introduced by random errors in the parameters used in emission calculations. Note logarithmic scale.

[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). Ebullition 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 [Olefelt *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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References

- Åberg, J., *et al.* (2007), Pelagic and benthic net production of dissolved inorganic carbon in an unproductive subarctic lake, *Freshwater Biol.*, 52, 549–560.
- Ask, J., *et al.* (2012), Net ecosystem production in clear-water and brown-water lakes, *Global Biogeochem. Cycles*, 26, GB1017, doi:10.1029/2010GB003951.
- Aufdenkampe, A. K., *et al.* (2011), Riverine coupling of biogeochemical cycles between land, oceans, and atmosphere, *Front. Ecol. Environ.*, 9(1), 53–60.
- Bartlett, K. B., *et al.* (1992), Methane emissions from tundra environments in the Yukon-Kuskokwim delta, Alaska, *J. Geophys. Res.*, 97(D15), 16,645–16,660.
- Bastviken, D., *et al.* (2004), Methane emissions from lakes: Dependence of lake characteristics, two regional assessments, and a global estimate, *Global Biogeochem. Cycles*, 18, GB4009, doi:10.1029/2004GB002238.
- Battin, T. J., *et al.* (2009), The boundless carbon cycle, *Nat. Geosci.*, 2(9), 598–600.
- Bertilsson, S., and L. J. Tranvik (2000), Photochemical transformation of dissolved organic matter in lakes, *Limnol. Oceanogr.*, 45(4), 753–762.

- Butman, D., and P. A. Raymond (2011), Significant efflux of carbon dioxide from streams and rivers in the United States, *Nat. Geosci.*, 4(12), 839–842.
- Christensen, T. R., et al. (2007), A catchment-scale carbon and greenhouse gas budget of a subarctic landscape, *Philos. Trans. R. Soc. London, Ser. A, Math. Phys. Eng. Sci.*, 365(1856), 1643–1656.
- Christensen, T. R., et al. (2012), Monitoring the multi-year carbon balance of a subarctic palsa mire with micrometeorological techniques, *Ambio*, 41, 207–217.
- Cole, J. J., and N. F. Caraco (1998), Atmospheric exchange of carbon dioxide in a low-wind oligotrophic lake measured by the addition of SF₆, *Limnol. Oceanogr.*, 43(4), 647–656.
- Cole, J. J., et al. (1994), Carbon-dioxide supersaturation in the surface waters of lakes, *Science*, 265(5178), 1568–1570.
- Crusius, J., and R. Wanninkhof (2003), Gas transfer velocities measured at low wind speed over a lake, *Limnol. Oceanogr.*, 48(3), 1010–1017.
- Dinsmore, K. J., et al. (2010), Role of the aquatic pathway in the carbon and greenhouse gas budgets of a peatland catchment, *Global Change Biol.*, 16(10), 2750–2762.
- Drugokencky, E. J., et al. (2009), Observational constraints on recent increases in the atmospheric CH₄ burden, *Geophys. Res. Lett.*, 36, 5, L18803, doi:10.1029/2009GL039780.
- Genereux, D. P., and H. F. Hemond (1992), Determination of gas-exchange rate constants for a small stream on Walker Branch watershed, Tennessee, *Water Resour. Res.*, 28(9), 2365–2374.
- Giesler, R., et al. (2013), Spatiotemporal variations of pCO₂ and ¹³C-DIC in subarctic streams in northern Sweden, *Global Biogeochem. Cycles*, 27, 1–11, doi:10.1002/gbc.20024.
- Hasan, A., et al. (2012), On generating digital elevation models from lidar data—Resolution versus accuracy and topographic wetness index indices in northern peatlands, *Geod. Cartography*, 38(2), 57–69.
- Hope, D., et al. (2001), Carbon dioxide and methane evasion from a temperate peatland stream, *Limnol. Oceanogr.*, 46(4), 847–857.
- Hope, D., et al. (2004), Variations in dissolved CO₂ and CH₄ in a first-order stream and catchment: An investigation of soil-stream linkages, *Hydrol. Processes*, 18(17), 3255–3275.
- Houghton, R. A. (2003), Why are estimates of the terrestrial carbon balance so different?, *Global Change Biol.*, 9(4), 500–509.
- Humborg, C., et al. (2010), CO₂ supersaturation along the aquatic conduit in Swedish watersheds as constrained by terrestrial respiration, aquatic respiration and weathering, *Global Change Biol.*, 16(7), 1966–1978.
- Intergovernmental Panel on Climate Change (2007), Climate Change 2007: The Physical Science Basis. *Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, 996 pp., Cambridge University Press, Cambridge, United Kingdom, New York, USA.
- Jähne, B., et al. (1987), On the parameters influencing air-water gas exchange, *J. Geophys. Res.*, 92(C2), 1937–1949.
- Johansson, M., et al. (2006), What determines the current presence or absence of permafrost in the Torneträsk region, a sub-arctic landscape in northern Sweden?, *Ambio*, 35(4), 190–197.
- Jonsson, A., et al. (2003), Sources of carbon dioxide supersaturation in clear-water and humic lakes in northern Sweden, *Ecosystems*, 6(3), 224–235.
- Jonsson, A., et al. (2008), Gas transfer rate and CO₂ exchange between an unproductive lake and the atmosphere in northern Sweden, *J. Geophys. Res.*, 113, G04006, doi:10.1029/2008JG000688.
- Karlsson, J. (2007), Different carbon support for community respiration and secondary production in unproductive lakes, *Oikos*, 116, 1691–1696.
- Karlsson, J., et al. (2010), Quantifying the relative importance of lake emissions in the carbon budget of a subarctic catchment, *J. Geophys. Res.*, 115, G03006, doi:10.1029/2010JG001305.
- Karlsson, J., et al. (2013), High emission of carbon dioxide and methane during ice thaw in high latitude lakes, *Geophys. Res. Lett.*, 40, 1–5, doi:10.1002/grl.50152.
- Kelly, C. A., and D. P. Chynoweth (1981), The contribution of temperature and of the input of organic matter in controlling rates of sediment methanogenesis, *Limnol. Oceanogr.*, 26(5), 891–897.
- Kling, G. W., et al. (1991), Arctic lakes and streams as gas conduits to the atmosphere: Implications for tundra carbon budgets, *Science*, 251(4991), 298–301.
- Kling, G. W., et al. (1992), The flux of CO₂ and CH₄ from lakes and rivers in arctic Alaska, *Hydrobiologia*, 240(1–3), 23–36.
- Koprivnjak, J. F., et al. (2010), Importance of CO₂ evasion from small boreal streams, *Global Biogeochem. Cycles*, 24, GB4003, doi: 10.1029/2009GB003723.
- Kuss, J., and B. Schneider (2004), Chemical enhancement of the CO₂ gas exchange at a smooth seawater surface, *Mar. Chem.*, 91(1–4), 165–174.
- Large, W. G., and S. Pond (1981), Open ocean momentum flux measurements in moderate to strong winds, *J. Phys. Oceanogr.*, 11(3), 324–336.
- Laurion, I., et al. (2010), Variability in greenhouse gas emissions from permafrost thaw ponds, *Limnol. Oceanogr.*, 55(1), 115–133.
- Malmer, N., et al. (2005), Vegetation, climatic changes and net carbon sequestration in a North-Scandinavian subarctic mire over 30 years, *Global Change Biol.*, 11(11), 1895–1909.
- Olefeldt, D., et al. (2012), Total waterborne carbon export and DOC composition from ten nested subarctic peatland catchments—Importance of peatland cover, groundwater influence, and inter-annual variability of precipitation patterns, *Hydrol. Processes*, 27(16), 2280–2294.
- Raymond, P. A., et al. (2012), Scaling the gas transfer velocity and hydraulic geometry in streams and small rivers, *Limnol. Oceanogr.: Fluids and Environ.*, 2, 41–53.
- Reeburgh, W. S., et al. (1998), A CH₄ emission estimate for the Kuparuk River basin, Alaska, *J. Geophys. Res.*, 103(D22), 29,005–29,013.
- Roots, E. F. (1989), Climate change: High-latitude regions, *Clim. Change*, 15(1–2), 223–253.
- Sarmiento, J. L., et al. (2010), Trends and regional distributions of land and ocean carbon sinks, *Biogeosciences*, 7(8), 2351–2367.
- Schuur, E. A. G., et al. (2009), The effect of permafrost thaw on old carbon release and net carbon exchange from tundra, *Nature*, 459(7246), 556–559.
- Serreze, M. C., and J. A. Francis (2006), The arctic amplification debate, *Clim. Change*, 76(3–4), 241–264.
- Striegl, R. G., et al. (2012), Carbon dioxide and methane emissions from the Yukon River system, *Global Biogeochem. Cycles*, 26, GB0E05, doi:10.1029/2012GB004306.
- Teodoru, C. R., et al. (2009), Patterns in pCO₂ in boreal streams and rivers of northern Quebec, Canada, *Global Biogeochem. Cycles*, 23, GB2012, doi:10.1029/2008GB003404.
- Tranvik, L. J., et al. (2009), Lakes and reservoirs as regulators of carbon cycling and climate, *Limnol. Oceanogr.*, 54(6), 2298–2314.
- Vachon, D., et al. (2010), The relationship between near-surface turbulence and gas transfer velocity in freshwater systems and its implications for floating chamber measurements of gas exchange, *Limnol. Oceanogr.*, 55(4), 1723–1732.
- Wallin, M. B., et al. (2011), Spatiotemporal variability of the gas transfer coefficient K_(CO2) in boreal streams: Implications for large scale estimates of CO₂ evasion, *Global Biogeochem. Cycles*, 25, GB3025, doi:10.1029/2010GB003975.
- Wallin, M. B., et al. (2013), Evasion of CO₂ from streams—The dominant component of the carbon export through the aquatic conduit in a boreal landscape, *Global Change Biol.*, 19(3), 785–797.
- Walter, K. M., et al. (2007), Thermokarst lakes as a source of atmospheric CH₄ during the last deglaciation, *Science*, 318(5850), 633–636.
- Walter, K. M., et al. (2008), Methane production and bubble emissions from arctic lakes: Isotopic implications for source pathways and ages, *J. Geophys. Res.*, 113, G00A08, doi:10.1029/2007JG000569.
- Wanninkhof, R. (1992), Relationship between wind speed and gas exchange over the ocean, *J. Geophys. Res.*, 97(C5), 7373–7382.
- Wanninkhof, R., and M. Knox (1996), Chemical enhancement of CO₂ exchange in natural waters, *Limnol. Oceanogr.*, 41(4), 689–697.