Large Lakes Dominate CO₂ Evasion From Lakes in an Arctic Catchment

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Abstract CO₂ evasion from freshwater lakes is an important component of the carbon cycle. However, the relative contribution from different lake sizes may vary, since several parameters underlying CO₂ flux are size dependent. Here we estimated the annual lake CO₂ evasion from a catchment in northern Sweden encompassing about 30,000 differently sized lakes. We show that areal CO₂ fluxes decreased rapidly with lake size, but this was counteracted by the greater overall coverage of larger lakes. As a result, total efflux increased with lake size and the single largest lake in the catchment dominated the CO₂ evasion (53% of all CO₂ evaded). By contrast, the contribution from the smallest ponds (about 27,000) was minor (<6%). Our results emphasize the importance of accounting for both CO₂ flux rates and areal contribution of various sized lakes in assessments of CO₂ evasion at the landscape scale.

1. Introduction

Inland waters play an important role in the global carbon (C) cycle, transporting C to oceans, burying C in sediments, and evading CH₄ and CO₂ to the atmosphere (Cole et al., 2007; Tranvik et al., 2009). Large changes of the landscape carbon balance can be expected in the arctic with the increasing global warming, potentially releasing large amount of C into the aquatic environment (Frey & Smith, 2005). It has been known that limnic systems also in the arctic are landscape net sources of greenhouse gases (Kling et al., 1991) and their role may therefore be enhanced. But while there have been major advances in our understanding of C fluxes in and from lakes (Battin et al., 2009; Holgerson & Raymond, 2016; Tranvik et al., 2009), important knowledge gaps remain. One key question is to what extent lake size affects the assessment of C evasion from lentic environments on a landscape scale. The lake size distribution has been described by a power law function (Downing & Prairie, 2006; Seekell et al., 2013), meaning that a tenfold increase of the lake area follows a decrease of the same magnitude of its abundance. Partitioning C evasion according to size distribution of lakes could thus be one important step improving landscape C balances.

The flux of CO₂ depends on two parameters that can be size dependent: the concentration of CO₂ in the water and the gas transfer velocity (k). Lakes are generally supersaturated with CO₂ (Cole et al., 1994) although there is typically a decreasing trend in lake CO₂ concentrations with increasing lake area (Holgerson & Raymond, 2016; Humborg et al., 2010; Kankaala et al., 2013). For k, which is a function of the turbulence of the aquatic-atmospheric interface, the kinematic viscosity, and the gas diffusion coefficient, wind serves the main energetic driver (Wanninkhof, 1992). As such, larger lakes are able to obtain a larger mean wave size that generates greater turbulence and k in surface waters (Read et al., 2012; Vachon et al., 2013). This opposing size dependency of CO₂ concentration and k raises the possibility that these factors could cancel each other out, such that CO₂ flux would be invariant with lake size. To what extent this is the case is, however, still not clear.

Yet even if CO₂ flux is inversely related to lake size, the significance of small ponds and lakes as sources to the atmosphere may also be constrained by their small overall areal cover at catchment scales. In the most recent global estimate of C evasion from lakes it was shown that ponds can be large contributors of CO₂; however, only one lake larger than 100 km² was included (Holgerson & Raymond, 2016). Also, there are globally more large lakes than previous thought (Verpoorter et al., 2014), and CO₂ fluxes appear to be underestimated for larger lakes (Seekell et al., 2014). There is a paucity of data addressing the role of lake size as a driver of C cycling and a need to more accurately quantify the role of larger lakes for the CO₂ evasion at the landscape level.
This study aims to determine the importance of CO₂ evasion across lake sizes in a catchment consisting of lakes ranging several orders of magnitude in area. Specifically, we assessed the relative contribution of one single large lake to the overall lake CO₂ evasion across different lake sizes, from ponds (lakes smaller than 0.001 km²) to several lakes larger than 10 km² and with the largest of 334.5 km². To do so, we determined the annual CO₂ evasion from the largest lake and, together with available data on CO₂ concentrations in lakes in the study area (Jonsson et al., 2003; Lundin et al., 2013), upscaled CO₂ fluxes from all lakes in the catchment. This enabled us to resolve the role of different lake size classes for the overall catchment CO₂ evasion and compare these with the more recent global estimates.

2. Methods

2.1. Site Description

The study site is the 3,290 km² Torneträsk catchment in northern Sweden (68.40°N 18.90°E; Figure 1a), about 200 km above the polar circle. The catchment is mountainous, with altitudes ranging between 350 and 1,750 m above sea level. Lakes cover about 15% of the catchment area of which 69% corresponds to Lake Torneträsk. Lake Torneträsk covers 334.5 km², is 70 km long and a maximum width of 11 km, and has an...
average depth of 52 m (www.smhi.se) and a maximum depth of 180 m. The water volume is 17.1 km$^3$; the water residence time is estimated to be about 8–12 years. Ice cover of Lake Torneträsk is generally between early January and late May (Callaghan et al., 2010). The mean annual air temperature is 0°C (1995–2006), measured at the Abisko Scientific Research Station, located at the southern shore of the lake. Lakes are generally clear water lakes, with dissolved organic carbon (DOC) concentrations ranging from 0.7 mg C L$^{-1}$ at high elevations to 10 mg C L$^{-1}$ in lakes forested areas or mire-influenced lakes, where lakes are slightly more colored (Jonsson et al., 2003; Karlsson et al., 2001). There is a clear precipitation gradient from west to east, with high precipitation (~900 mm) in the western part but also a smoother temperature variation along the year, due to the oceanic influence (Åkerman & Johansson, 2008). Hence, the climate is more continental and drier in the eastern side of the catchment, with a precipitation minimum in the Abisko valley (340 mm). Forest cover is dominated by mountain birch forests (*Betula pubescens* spp. *czeperanovii*) in the lower altitudes with some patches of Scots pine (*Pinus sylvestris*) in the east. The tree line is around 650 m (Holmgren & Tjus, 1996), and tundra vegetation is found above the tree line. Discontinuous permafrost can be found above 800 m (Gisnås et al., 2017) and on mires and exposed areas at lower altitudes (Åkerman & Johansson, 2008). At higher elevations some glaciers and snow fields are present.

### 2.2. Lake Inventory

A 50 m resolution digital elevation model (DEM) of the Torneträsk area was obtained from Lantmäteriet (http://www.lantmateriet.se), and the boundary of the catchment was determined based on the DEM and outlet point of the catchment applying watershed modeling in ArcGIS 10. The global lake inventory was obtained from the most recent estimate of lakes (Verpoorter et al., 2014). The definition used here is that ponds are water bodies smaller than 0.001 km$^2$ and lakes >0.001 km$^2$ following the size categories in Verpoorter et al., 2014. The mean altitude of each lake was determined using the zonal analysis tool in ArcGIS 10. A small portion of lakes (n = 16, representing 0.06 % of the total catchment lake area) on the Norwegian side of the Torneträsk catchment were measured manually with satellite images and ArcGIS measure tool, as they were not included in the data provided. Due to the resolution of the data, ponds under 1,000 m$^2$ were not present in the lakes map. To estimate the number and total area of these ponds, we used orthophoto imagery of the catchment (http://www.lantmateriet.se; 2 m resolution) to manually measure the area and count these ponds for four different subcatchments. In total, 225.5 km$^2$ was surveyed and 2,450 ponds were measured and counted. To estimate the area of ponds in the whole catchment, we extrapolated the pond density and distribution to the whole catchment. Details about the estimate of the enumeration of ponds are found in Text S1 in the supporting information.

### 2.3. Flux Calculations

To upscale annual CO$_2$ fluxes from all lakes of the catchment, we measured CO$_2$ concentration in Lake Torneträsk and combined these data with published values from small to intermediate sized lakes in this catchment. For Lake Torneträsk, we measured CO$_2$ concentration in the water continuously in 2012 using an infrared gas analyzer (IRGA; Vaisala CARBOCAP, GMT220, Helsinki, Finland, as in Johnson et al., 2010) during the ice-free season until mid-October. The raft with the IRGA was placed as far from the shore as possible where it could be anchored, at around 20 m depth, located at 1.4 km from the shoreline and 300 m from an island (location shown in Figure S2). In addition, to assess the spatial variability in CO$_2$ concentration, we sampled at 17 locations during 3 occasions (April before ice breakup, July, and August). The Lake Torneträsk is very deep (average depth of 52 m) and assumed to be dominated by pelagic carbon fluxes. More details about the sampling in Lake Torneträsk are found in Text S2.

Jonsson et al. (2003) measured pCO$_2$ in 16 lakes, monthly during the summer 2000. We used the average pCO$_2$ of the 3 months to obtain a mean pCO$_2$ for each of these. Lundin et al. (2013) sampled another set of 26 lakes in the catchment, monthly during the ice-free season of 2009. Twelve of these lakes were also sampled to estimate the evasion during the ice-thaw in the spring (Karlsson et al., 2013). Finally, the second largest lake in the catchment, Lake Vassijaure (16.7 km$^2$), was measured during the 19 June until 19 September of the year 2006 by surface CO$_2$ measurements performed every hour on a raft (for method details; Jonsson et al., 2007). In total, we gathered CO$_2$ measured across seasons in 45 lakes in the Torneträsk catchment, including lakes of all sizes and comprising 70.9% of the total catchment lake area. In 26 of these lakes (studied in Lundin et al., 2013) and in Lake Torneträsk, measurements before the ice
breakup and the autumn were included, capturing potentially high CO2 fluxes at ice-break up and autumn turnover, although the weak stratification in lakes in this region suggests that effects of the autumn turnover can be small (Jonsson et al., 2003).

The gas exchange between the atmosphere and the water surface, $F_{CO2}$, is defined by

$$F_{CO2} = \epsilon k_t(CO2_{water} - CO2_{air}),$$

where $CO2_{water}$ is the partial pressure of CO2 in the water, $CO2_{air}$ the pCO2 in the air (set to 380 ppm based on measurements in 2012), and $\epsilon$ the chemical enhancement factor (Kuss & Schneider, 2004). $k_t$ is the gas transfer velocity at a certain water temperature, obtained from

$$k_t = k_{600} \left( \frac{Sc_t}{Sc_{600}} \right)^n,$$

where $Sc_t$ is the Schmidt number at the particular temperature calculated as in Wanninkhof (1992), assuming the Schmidt number exponent $n = -1/2$ (Jähne & Haußeker, 1998). $k_{600}$ is the gas transfer velocity standardized for a Schmidt number of 600. The gas transfer velocity depends on the turbulence of the top layer of the water. This has best been described by using wind speed as a predictor (e.g., Cole et al., 1994; Wanninkhof (1992)), but several other factors can be important (MacIntyre et al., 2010; Harrison et al., 2012; Read et al., 2012). It is clear that many factors affect the gas transfer velocity from a specific lake, which are not easily transferred into large-scale modeling. However, a recent study compared different $k_{600}$ models (Vachon et al., 2013) and found that the best relationship was obtained when including the wind speed and lake area (LA):

$$k_{600} = 2.51(\pm0.99) + 1.48(\pm0.34) \cdot U_{10} + 0.39(\pm0.08) \cdot U_{10} \cdot \log_{10}(LA),$$

where $U_{10}$ is the wind speed at the height of 10 m. This is particularly useful for upscaling as lake area is a simple and available predictor, and we therefore used equation (3) to calculate $k_{600}$ for each lake, with the average mean wind speed measured at the Abisko research station during the summer 2012 and summer 2013.

To calculate CO2 fluxes for all the lakes of the catchment, we predicted key variables required for the calculation of annual CO2 fluxes. We used a power law relationship between the lake area and the pCO2 of lakes smaller than 1 km$^2$ ($R^2 = 0.44$; linear regression on log-transformed data, Table S1) that was used to predict the pCO2 of all lakes smaller than 1 km$^2$. For the larger lakes ($n = 22$) except Lake Torneträsk, we used the mean pCO2 of the measured lakes larger than 1 km$^2$ ($n = 2$). Although we have no CO2 data for lakes under 1,000 m$^2$, the estimated values are in range with literature (Holgerson & Raymond, 2016; Pokrovsky et al., 2013). Together with other variables such as lake temperature, the $k_{600}$, and the length of the ice-free season, we estimated a yearly CO2 flux and, by a Monte-Carlo simulation for each individual lake, the uncertainty of our calculations. More details about the upscaling are found in supporting information Text S3.

### 3. Results

#### 3.1. Lake Distribution in the Torneträsk Catchment

In the Torneträsk catchment there are 3,184 lakes larger than 0.001 km$^2$ and about 27,070 ponds (lakes smaller than 0.001 km$^2$). Although ponds are 74.8% of all lakes in the catchment, they account only for 1.8% of the total lake area, while the largest lake (Lake Torneträsk) accounts for 64.3% of the total catchment lake area (Table S2). Across elevations, the largest number of lakes lie between 400 and 600 m (41.2%), while above 600 m the number of lakes decreases (Figure S3). Since Lake Torneträsk and the other larger lakes in the catchment are located below 400 m, a majority (75.4%) of the total lake area is found below 400 m.

#### 3.2. Lake Torneträsk

Average winter CO2 concentration in Lake Torneträsk was $35 \pm 4 \mu M$ (average $\pm$ 2 standard deviation (SD)), DOC concentration was $115 \pm 25 \mu M$, and dissolved inorganic carbon (DIC) concentration was
Lake Torneträsk was a yearly source of CO₂, evading 6.6 ± 0.9 g C m⁻² yr⁻¹. On a monthly basis the CO₂ flux was high 1.4 g C m⁻² month⁻¹ in July compared to August (0.18 g C m⁻² month⁻¹) and September (0.82 g C m⁻² month⁻¹).

3.3. Upscaling Fluxes From Lakes in the Torneträsk Catchment

After upscaling CO₂ concentrations for all lakes in the catchment, we found that most lakes were sources of CO₂ to the atmosphere (Figure 3) with only 77 lakes (0.2% of all lakes) being undersaturated with CO₂. The smallest ponds (area about 10 m²) had the highest variability in CO₂ concentration, ranging between 100 and 150 μM. There was a decreasing trend in CO₂ concentration with lake area, with a threshold around a lake size of 1 km² where the CO₂ concentration remained stable around 25 μM regardless of an increasing lake area.

The \( k_{\text{GM}} \) modeled from lake area and wind, was 2.2 cm h⁻¹ in the lake size class under 0.001 km², for the 0.001–0.01 km², 0.01–0.1 km², 0.1–1 km², 1–10 km², the \( k_{\text{GM}} \) was 3.0, 3.5, 4.1, 5.1, and 5.8 cm h⁻¹ respectively, and for Lake Torneträsk was 6.3 cm h⁻¹ (Table S2). The CO₂ fluxes for different lake sizes decreased with area for lakes under 100 km² (Figure 4); however, due to the higher \( k_{\text{GM}} \) we observed a relatively greater CO₂ fluxes for Lake Torneträsk. For ponds (lakes <0.001 km²) the median CO₂ flux was 17.3 g C m⁻² yr⁻¹, while for lakes of 1–10 km² area class the flux was 6.2 g C m⁻² yr⁻¹. In total, lakes in the Torneträsk catchment emitted 4.1 Gg C yr⁻¹, which was a flux equivalent to 7.9 g C m⁻² yr⁻¹ per lake area and 1.3 g C m⁻² yr⁻¹ per catchment area. At the catchment scale we found that Lake Torneträsk emitted 2.18 Gg C yr⁻¹ which was 53% of the total amount of CO₂ evaded by lakes in the catchment. In contrast, ponds were responsible for 5% (0.2 Gg C yr⁻¹) lakes between 0.001 and 1 km² for 19% (1 Gg C yr⁻¹) and lakes between 1 and 100 km² for 15% (0.6 Gg C yr⁻¹) of total lake CO₂ fluxes.

4. Discussion

Lake size has an important effect on the CO₂ evasion: terrestrial C inputs and lake pCO₂ will decrease with lake size (Jansson et al., 2008), while \( k \) will increase with larger water bodies that can capture more energy from the wind (Vachon et al., 2013). The interaction between pCO₂ and \( k \) and how different lake size classes are represented in the
landscape determines the role of lakes for CO₂ evasion. Our study shows that the large Lake Torneträsk dominates CO₂ evasion from the catchment, in spite of having threefold lower areal fluxes than ponds.

The role of ponds versus larger lakes in the C cycle has been recently discussed (Downing, 2010; Holgerson & Raymond, 2016), closely following the question of whether small or large lakes dominate the global lake area, which has been discussed for nearly a century (Downing & Prairie, 2006; Seekell et al., 2013; Thiemann, 1926; Verpoorter et al., 2014). While initial studies suggested that large lakes account for most of the lake area (Thieman, 1926), the first attempt to quantify the global lake size distribution found that the total lake area is dominated by small lakes and ponds (Downing & Prairie, 2006). It was not until the satellite era that lakes could be measured at a global scale, and these more recent efforts have shown that there are more large lakes than expected and that these indeed account for a larger fraction of the total lake area (Verpoorter et al., 2014).

The Torneträsk catchment is located in the arctic, at a latitude where the highest abundance of lakes is expected (Verpoorter et al., 2014). Indeed, there are more than 30,000 lakes in the Torneträsk catchment, covering 15.6% of the drainage area. The large (334.5 km²) Lake Torneträsk accounts for 64% of the total lake area in the catchment and thus represents a higher share when compared to the global average (Figure 1a). Although the proportion of large water bodies in our study catchment is higher than the global average, it can be noted that in other arctic areas such as pond rich regions of Siberia, larger lakes also dominate the lake area (Grosse et al., 2008).

For lakes in the Torneträsk catchment, the CO₂ concentrations were generally lower than in other studies (Holgerson & Raymond, 2016; Humborg et al., 2010), presumably due to the low productivity of the arctic landscape and therefore reduced terrestrial C export to lakes (Jansson et al., 2008). The decreasing trend of pCO₂ with lake area is in accordance with findings in other high-latitude regions (Kankaala et al., 2013), presumably mainly reflecting decreased areal specific terrestrial C input and also increased k, with lake size. However, Lake Torneträsk was supersaturated in CO₂ throughout the year, particularly during winter, after the ice break and during the autumn (Figure 2). For small lakes in this catchment it has been shown that the CO₂ fluxes after the ice break can account for up to 55% of the annual CO₂ flux (Karlsson et al., 2013).

In the case of Torneträsk, early summer and particularly autumn periods are responsible for most of the CO₂ evasion throughout the year, as has been shown previously in boreal lakes (López Bellido et al., 2009). Compared to CO₂ concentrations, the effect of lake size is more direct for k, as bigger lakes will be able to produce larger waves under the effect of wind, the main driver of k. In our study and according to the model used (equation (3)), k follows a logarithmic increase with area (Vachon et al., 2010). Besides the main driver, wind, other factors such as buoyancy flux and precipitation can affect k in lakes (Harrison et al., 2012; MacIntyre et al., 2010). Especially convection can be important for small lakes (Read et al., 2012), although there is still a lack of models to incorporate these factors on k across scales.

The interaction between pCO₂ and k₆₃₀₀ across different lake sizes determines the CO₂ flux, and both parameters have opposite, nonlinear trends with lake area. Thus, accounting for these relationships is a vital step toward upscaling CO₂ evasion from lakes, and in our study we find that the net effect is a decreasing areal CO₂ flux with increasing lake size. Previous attempts at large scale estimates of CO₂ evasion from lakes have used a product-of-means approach (Aufdenkampe et al., 2011; Marotta et al., 2009), which can cause large errors due to the covariance of concentration and gas transfer rate over size scale of lakes (Seekell et al., 2014). Particularly across Swedish lakes, this approach can overestimate CO₂ evasion by 4% for small lakes and underestimate the evasion from lakes larger than 100 km² by 13% (Seekell et al., 2014). To give a better estimate, we predicted both pCO₂ and k₆₃₀₀ for each lake of the catchment, based on the area and elevation of lakes. Our results highlight that large lakes, although having lower pCO₂, can be still greater sources of CO₂ than medium sized lakes. Moreover, the role of large lakes is more relevant when considering that they dominate the lentic coverage, both in the Torneträsk catchment and globally (Figure 1b).

In our study we did not have sufficient data to include a thorough assessment of the size dependency of lake CH₄ fluxes. CH₄ was not observed in any samples in Lake Torneträsk, independently of sampling depth or season. Also, a recent sediment survey from Lake Torneträsk found consistently oxygenated water above the sediments (H. Vogel, personal communication, 2014), suggesting that CH₄ produced in the sediment is likely oxidized before reaching the lake surface. Another study measured both CO₂ and CH₄ fluxes from small lakes
in a mire-rich catchment in the Torneträsk basin and found that CH4 represent 20% of annual C emissions from these lakes (Lundin et al., 2013), but this is likely not representative of all lakes in the catchment due to the large influence of mires, which are not ubiquitous in the catchment. Holgerson and Raymond (2016) showed that the ratio between the CO2 and CH4 has a strong dependence on lake area, varying between 1.7 in ponds <0.001 km² and 22.4 for lakes between 10 and 100 km². Using the published ratios for different lake size classes (Holgerson & Raymond, 2016), we calculate a total CH4 flux from all lakes except Lake Torneträsk of 0.29 Gg C yr⁻¹, of which ponds (<0.001 km²) are responsible for 43%. This implies that ponds account for 7.9% of total C fluxes, instead of 5.6% without including CH4 fluxes, and that Lake Torneträsk is still the main source of atmospheric C from lakes (Table S2). Although these estimates include large potential uncertainties of CH4 fluxes across lake sizes, it does suggest that the overall patterns in C evasion across lake sizes is robust.

Our study offers important insights of the size dependency of lake C evasion in arctic regions. Although small ponds were hot spots with much higher areal CO2 fluxes than larger lakes, large lakes account for most of the lake area and thus dominated lake CO2 evasion at the catchment scale. Our results stress the need of accounting for both changes in flux rates and areal coverage of various sized lakes for accurate assessments of CO2 evasion beyond the scale of individual lakes.

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