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Key Points:
- The parameters of CO_2 evasion from lakes are area dependent, with opposite nonlinear trends
- The large lakes due to the large area and high gas transfer velocity dominate the CO_2 evasion to the atmosphere
- Ponds have high areal CO_2 fluxes but low area coverage, with a low impact on total CO_2 evaded

Supporting Information:
- Supporting information S1

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Large Lakes Dominate CO_2 Evasion From Lakes in an Arctic Catchment

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Abstract CO_2 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 CO_2 flux are size dependent. Here we estimated the annual lake CO_2 evasion from a catchment in northern Sweden encompassing about 30,000 differently sized lakes. We show that areal CO_2 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 CO_2 evasion (53% of all CO_2 evaded). By contrast, the contribution from the smallest ponds (about 27,000) was minor (<6%). Our results emphasize the importance of accounting for both CO_2 flux rates and areal contribution of various sized lakes in assessments of CO_2 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 CH_4 and CO_2 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 CO_2 depends on two parameters that can be size dependent: the concentration of CO_2 in the water and the gas transfer velocity (k). Lakes are generally supersaturated with CO_2 (Cole et al., 1994) although there is typically a decreasing trend in lake CO_2 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 CO_2 concentration and k raises the possibility that these factors could cancel each other out, such that CO_2 flux would be invariant with lake size. To what extent this is the case is, however, still not clear.

Yet even if CO_2 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 CO_2; however, only one lake larger than 100 km^2 was included (Holgerson & Raymond, 2016). Also, there are globally more large lakes than previous thought (Verpoorter et al., 2014), and CO_2 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 CO_2 evasion at the landscape level.

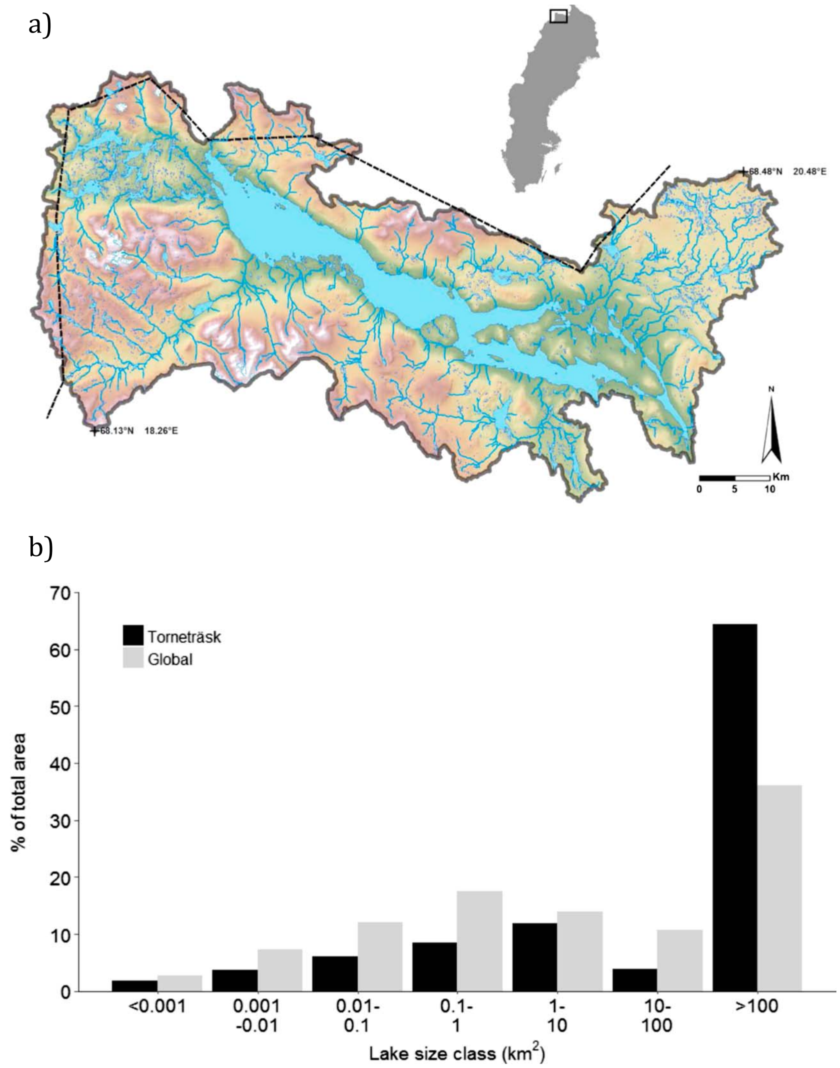

Figure 1. (a) Map of Torneträsk catchment in northern Sweden with Lake Torneträsk in the center of the figure. The dotted line shows the Swedish-Norwegian border. (b) Distribution of total lake area across lake size classes in the Torneträsk catchment and globally (data from Verpoorter et al., 2014).

This study aims to determine the importance of CO_2 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 CO_2 evasion across different lake sizes, from ponds (lakes smaller than 0.001 km^2) to several lakes larger than 10 km^2 and with the largest of 334.5 km^2. To do so, we determined the annual CO_2 evasion from the largest lake and, together with available data on CO_2 concentrations in lakes in the study area (Jonsson et al., 2003; Lundin et al., 2013), upscaled CO_2 fluxes from all lakes in the catchment. This enabled us to resolve the role of different lake size classes for the overall catchment CO_2 evasion and compare these with the more recent global estimates.

2. Methods

2.1. Site Description

The study site is the 3,290 km^2 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 km^2, 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. *czerepanovii)* 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

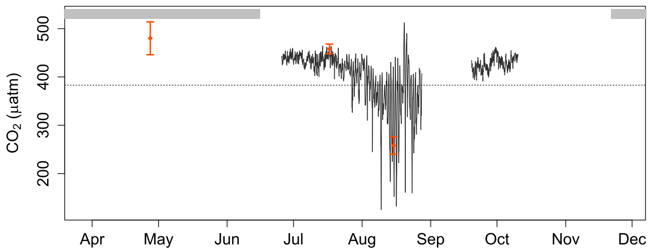

Figure 2. Surface water pCO_2 in Lake Torneträsk during 2012 based on logger data at one point (solid line) and mean (+1 2 SD) of snap shot measurements across the lake (orange points). The gap in the data is the period when the IRGA remained inoperative between 28 August and 19 September due to a storm. The dotted line shows the atmospheric pCO_2, and the top gray line shows the extent of the ice cover period.

breakup and the autumn were included, capturing potentially high CO_2 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_{CO_2}, is defined by

$$F_{CO_2} = \varepsilon\, k_t(CO_{2_{water}} - CO_{2_{air}}), \tag{1}$$

where $CO_{2_{water}}$ is the partial pressure of CO_2 in the water, $CO_{2_{air}}$ the pCO_2 in the air (set to 380 ppm based on measurements in 2012), and ε the chemical enhancement factor (Kuss & Schneider, 2004). k_t is the gas transfer velocity at a certain water temperature, obtained from

$$k_t = k_{600}\left(\frac{Sc_t}{Sc_{600}}\right)^n, \tag{2}$$

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 & Haußecker, 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):

$$k_{600} = 2.51(\pm 0.99) + 1.48(\pm 0.34)\cdot U_{10} + 0.39(\pm 0.08)\cdot U_{10}\cdot \log_{10}(\mathrm{LA}), \tag{3}$$

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 CO_2 fluxes for all the lakes of the catchment, we predicted key variables required for the calculation of annual CO_2 fluxes. We used a power law relationship between the lake area and the pCO_2 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 pCO_2 of all lakes smaller than 1 km^2. For the larger lakes (n = 22) except Lake Torneträsk, we used the mean pCO_2 of the measured lakes larger than 1 km^2 (n = 2). Although we have no CO_2 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 CO_2 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 CO_2 concentration in Lake Torneträsk was 35 ± 4 µM (average ± 2 standard deviation (SD)), DOC concentration was 115 ± 25 µM, and dissolved inorganic carbon (DIC) concentration was

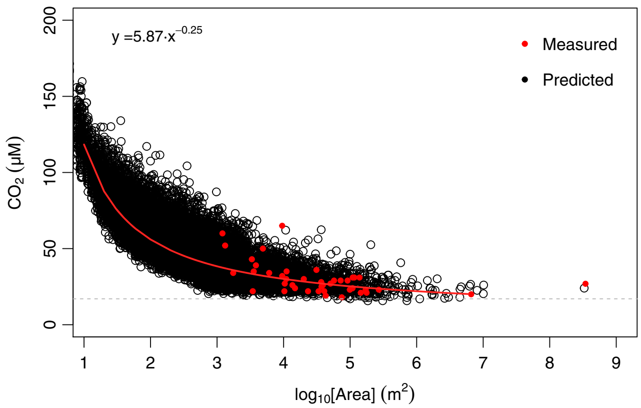

Figure 3. Surface water CO_2 concentration of all lakes of the Torneträsk catchment, showing both measured (red) and estimated (black) values. The red line denotes the power law fits of the measured values, used for the upscaling. The dotted line shows atmospheric CO_2 concentration.

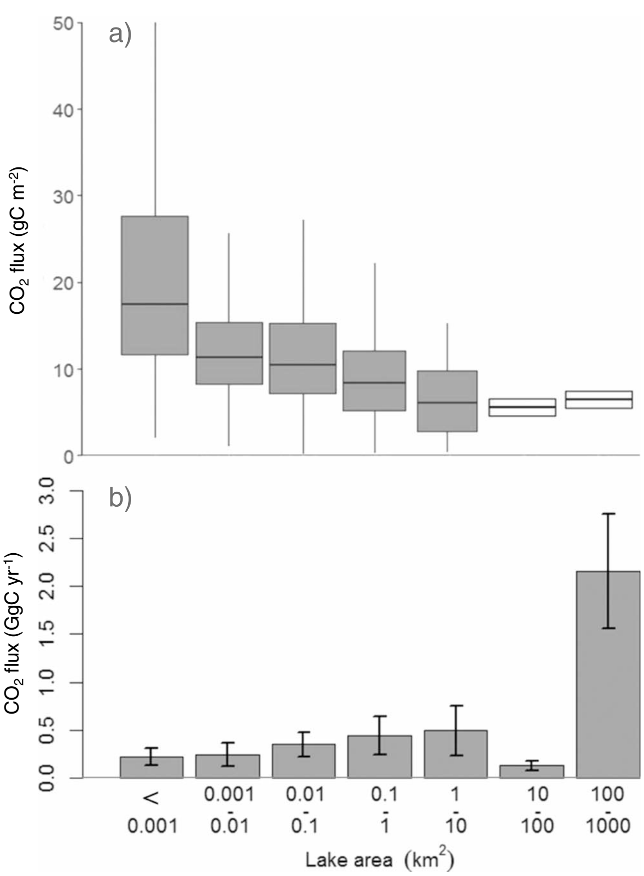

Figure 4. (a) Box plot of modeled yearly CO_2 fluxes for different lake size classes. For the class 10–100 km^2 and 100–1,000 km^2 the number of lakes was 2 and 1, respectively, and for these classes the line represents the mean value of the flux of the lake and the box size represents ±2 SD obtained from the Monte-Carlo simulation. (b) Cumulative yearly CO_2 flux for each lake size class. Error bars represent the 95% confidence interval.

279 ± 28 μ*M*. CH_4 was below detection limit (2 ppm) in all samples. We found no relationship between carbon species (DOC, DIC, and CO_2) and physical characteristics of the lake, such as water temperature, depth, or distance to shoreline. After the ice breakup, 15 June, the CO_2 concentrations were about 34 μ*M* and remained stable for the first weeks until mid-July (Figure 2). During the spatial sampling in July, the mean CO_2 concentration was 33 ± 2 μ*M*, with no significant differences with winter concentrations (*t* test; *p* value <0.01). CO_2 concentrations showed a diel variation with increasing amplitudes during August, reaching a maximum difference between day and night of 26 μ*M* the 20 August (Figure S5). Although there was a decreasing trend in CO_2 from June to August, nighttime CO_2 were still supersaturated (Figure 2).

Lake Torneträsk was a yearly source of CO_2, evading 6.6 ± 0.9 g C m^{-2} yr^{-1} On a monthly basis the CO_2 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 CO_2 concentrations for all lakes in the catchment, we found that most lakes were sources of CO_2 to the atmosphere (Figure 3) with only 77 lakes (0.2% of all lakes) being undersaturated with CO_2. The smallest ponds (area about 10 m^2) had the highest variability in CO_2 concentration, ranging between 100 and 150 μ*M*. There was a decreasing trend in CO_2 concentration with lake area, with a threshold around a lake size of 1 km^2 where the CO_2 concentration remained stable around 25 μ*M* regardless of an increasing lake area.

The k_{600}, modeled from lake area and wind, was 2.2 cm h^{-1} in the lake size class under 0.001 km^2, for the 0.001–0.01 km^2, 0.01–0.1 km^2, 0.1–1 km^2, 1–10 km^2, the k_{600} 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 CO_2 fluxes for different lake sizes decreased with area for lakes under 100 km^2 (Figure 4); however, due to the higher k_{600}, we observed a relatively greater CO_2 fluxes for Lake Torneträsk. For ponds (lakes <0.001 km^2) the median CO_2 flux was 17.3 g C m^{-2} yr^{-1}, while for lakes of 1–10 km^2 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 CO_2 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 km^2 for 19% (1 Gg C yr^{-1}) and lakes between 1 and 100 km^2 for 15% (0.6 Gg C yr^{-1}) of total lake CO_2 fluxes.

4. Discussion

Lake size has an important effect on the CO_2 evasion: terrestrial C inputs and lake pCO_2 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 pCO_2 and *k* and how different lake size classes are represented in the landscape determines the role of lakes for CO_2 evasion. Our study shows that the large Lake Torneträsk dominates CO_2 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; Thienemann, 1926; Verpoorter et al., 2014). While initial studies suggested that large lakes account for most of the lake area (Thienemann, 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 km^2) 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 CO_2 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 pCO_2 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 CO_2 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 CO_2 fluxes after the ice break can account for up to 55% of the annual CO_2 flux (Karlsson et al., 2013). In the case of Torneträsk, early summer and particularly autumn periods are responsible for most of the CO_2 evasion throughout the year, as has been shown previously in boreal lakes (López Bellido et al., 2009).

Compared to CO_2 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 pCO_2 and k_{600} across different lake sizes determines the CO_2 flux, and both parameters have opposite, nonlinear trends with lake area. Thus, accounting for these relationships is a vital step toward upscaling CO_2 evasion from lakes, and in our study we find that the net effect is a decreasing areal CO_2 flux with increasing lake size. Previous attempts at large scale estimates of CO_2 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 CO_2 evasion by 4% for small lakes and underestimate the evasion from lakes larger than 100 km^2 by 13% (Seekell et al., 2014). To give a better estimate, we predicted both pCO_2 and k_{600} for each lake of the catchment, based on the area and elevation of lakes. Our results highlight that large lakes, although having lower pCO_2, can be still greater sources of CO_2 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 CH_4 fluxes. CH_4 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 CH_4 produced in the sediment is likely oxidized before reaching the lake surface. Another study measured both CO_2 and CH_4 fluxes from small lakes in a mire-rich catchment in the Torneträsk basin and found that CH_4 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 CO_2 and CH_4 has a strong dependence on lake area, varying between 1.7 in ponds <0.001 km^2 and 22.4 for lakes between 10 and 100 km^2. Using the published ratios for different lake size classes (Holgerson & Raymond, 2016), we calculate a total CH_4 flux from all lakes except Lake Torneträsk of 0.29 Gg C yr^{-1}, of which ponds (<0.001 km^2) are responsible for 43%. This implies that ponds account for 7.9% of total C fluxes, instead of 5.6% without including CH_4 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 CH_4 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 CO_2 fluxes than larger lakes, large lakes account for most of the lake area and thus dominated lake CO_2 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 CO_2 evasion beyond the scale of individual lakes.

Acknowledgments

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References

Åkerman, H. J., & Johansson, M. (2008). Thawing permafrost and thicker active layers in sub-arctic Sweden. *Permafrost and Periglacial Processes*, *19*, 279–292. https://doi.org/10.1002/ppp.626

Aufdenkampe, A. K., Mayorga, E., Raymond, P. A., Melack, J. M., Doney, S. C., Alin, S. R., … Yoo, K. (2011). Riverine coupling of biogeochemical cycles between land, oceans, and atmosphere. *Frontiers in Ecology and the Environment*, *9*, 53–60.

Battin, T. J., Luyssaert, S., Kaplan, L. a., Aufdenkampe, A. K., Richter, A., & Tranvik, L. J. (2009). The boundless carbon cycle. *Nature Geoscience*, *2*, 598–600. https://doi.org/10.1038/ngeo618

Callaghan, T. V., Bergholm, F., Christensen, T. R., Jonasson, C., Kokfelt, U., & Johansson, M. (2010). A new climate era in the sub-Arctic: Accelerating climate changes and multiple impacts. *Geophysical Research Letters*, *37*, L14705. https://doi.org/10.1029/2009GL042064

Cole, J. J., Caraco, N. F., Kling, G. W., & Kratz, T. K. (1994). Carbon dioxide supersaturation in the surface waters of lakes. *Science*, *265*(5178), 1568–1570. https://doi.org/10.1126/science.265.5178.1568

Cole, J. J., Prairie, Y. T., Caraco, N. F., McDowell, W. H., Tranvik, L. J., Striegl, R. G., … Melack, J. (2007). Plumbing the global carbon cycle: Integrating inland waters into the terrestrial carbon budget. *Ecosystems*, *10*, 171–184. https://doi.org/10.1007/s10021-006-9013-8

Downing, J., & Prairie, Y. T. (2006). The global abundance and size distribution of lakes, ponds, and impoundments. *Limnology and Oceanography*, *51*, 2388–2397. https://doi.org/10.4319/lo.2006.51.5.2388

Downing, J. A. (2010). Emerging global role of small lakes and ponds: Little things mean a lot. *Limnetica*, *29*, 9–24.

Frey, K. E., & Smith, L. C. (2005). Amplified carbon release from vast West Siberian peatlands by 2100. *Geophysical Research Letters*, *32*, L09401. https://doi.org/10.1029/2004GL022025

Gisnås, K., Etzelmüller, B., Lussana, C., Hjort, J., Sannel, A. B. K., Isaksen, K., … Åkerman, J. (2017). Permafrost map for Norway, Sweden and Finland. *Permafrost and Periglacial Processes*, *28*(2), 359–378. https://doi.org/10.1002/ppp.1922

Grosse, G., Romanovsky, V. E., Walter, K., Morgenstern, A., Lantuit, H., & Zimov, S. A. (2008). Distribution of thermokarst lakes and ponds at three yedoma sites in Siberia, Ninth International Conferencnce on Permafrost, 551–556.

Harrison, E. L., Veron, F., Ho, D. T., Reid, M. C., Orton, P., & McGillis, W. R. (2012). Nonlinear interaction between rain- and wind-induced air-water gas exchange. *Journal of Geophysical Research*, *117*, C03034. https://doi.org/10.1029/2011JC007693

Holgerson, M. A., & Raymond, P. A. (2016). Large contribution to inland water CO_2 and CH_4 emissions from very small ponds. *Nature Geoscience*, *9*(3), 222–226. https://doi.org/10.1038/ngeo2654

Holmgren, B., & Tjus, M. (1996). Summer air temperatures and tree line dynamics at Abisko. *Ecological Bulletins*, *45*, 159–169.

Humborg, C., Mörth, C.-M., Sundbom, M., Borg, H., Blenckner, T., Giesler, R., & Ittekkot, V. (2010). CO_2 supersaturation along the aquatic conduit in Swedish watersheds as constrained by terrestrial respiration, aquatic respiration and weathering. *Global Change Biology*, *16*(7), 1966–1978. https://doi.org/10.1111/j.1365-2486.2009.02092.x

Jähne, B., & Haußecker, H. (1998). Air-water gas exchange. *Annual Review of Fluid Mechanics*, *30*, 443–468.

Jansson, M., Hickler, T., Jonsson, A., & Karlsson, J. (2008). Links between terrestrial primary production and bacterial production and respiration in lakes in a climate gradient in subarctic Sweden. *Ecosystems*, *11*, 367–376. https://doi.org/10.1007/s10021-008-9127-2

Johnson, M. S., Billett, M. F., Dinsmore, K. J., Wallin, M., Dyson, K. E., & Jassal, R. S. (2010). Direct and continuous measurement of dissolved carbon dioxide in freshwater aquatic systems—Method and applications. *Ecohydrology*. https://doi.org/10.1002/eco

Jonsson, A., Aberg, J., & Jansson, M. (2007). Variations in pCO_2 during summer in the surface water of an unproductive lake in northern Sweden. *Tellus B*, *59*(5), 797–803. https://doi.org/10.1111/j.1600-0889.2007.00307.x

Jonsson, A., Karlsson, J., & Jansson, M. (2003). Sources of carbon dioxide supersaturation in clearwater and humic lakes in northern Sweden. *Ecosystems*, *6*(3), 224–235. https://doi.org/10.1007/s10021-002-0200-y

Kankaala, P., Huotari, J., Tulonen, T., & Ojala, A. (2013). Lake-size dependent physical forcing drives carbon dioxide and methane effluxes from lakes in a boreal landscape. *Limnology and Oceanography*, *58*(6), 1915–1930. https://doi.org/10.4319/lo.2013.58.6.1915

Karlsson, J., Giesler, R., Persson, J., & Lundin, E. J. (2013). High emission of carbon dioxide and methane during ice-thaw in high latitude lakes. *Geophysical Research Letters*, *40*, 1123–1127. https://doi.org/10.1002/grl.50152

Karlsson, J., Jonsson, A., & Jansson, M. (2001). Bacterioplankton production in lakes along an altitude gradient in the subarctic north of Sweden. *Microbial Ecology*, *42*(3), 372–382. https://doi.org/10.1007/s00248-001-0009-9

Kling, G. W., Kipphut, G. W., & Miller, M. C. (1991). Arctic lakes and streams as gas conduits to the atmosphere: Implications for tundra carbon budgets. *Science*, *251*(4991), 298–301. https://doi.org/10.1126/science.251.4991.298

Kuss, J., & Schneider, B. (2004). Chemical enhancement of the CO_2 gas exchange at a smooth seawater surface. *Marine Chemistry*, *91*, 165–174. https://doi.org/10.1016/j.marchem.2004.06.007

López Bellido, J., Tulonen, T., Kankaala, P., & Ojala, A. (2009). CO_2 and CH_4 fluxes during spring and autumn mixing periods in a boreal lake (Pääjärvi, southern Finland). *Journal of Geophysical Research*, *114*, G04007. https://doi.org/10.1029/2009JG000923

Lundin, E. J., Giesler, R., Persson, A., Thompson, M. S., & Karlsson, J. (2013). Integrating carbon emissions from lakes and streams in a subarctic catchment. *Journal of Geophysical Research: Biogeosciences*, *118*, 1200–1207. https://doi.org/10.1002/jgrg.20092

MacIntyre, S., Jonsson, A., Jansson, M., Aberg, J., Turney, D. E., & Miller, S. D. (2010). Buoyancy flux, turbulence, and the gas transfer coefficient in a stratified lake. *Geophysical Research Letters*, *37*, L24604. https://doi.org/10.1029/2010GL044164

Marotta, H., Duarte, C. M., Sobek, S., & Enrich-Prast, A. (2009). Large CO_2 disequilibria in tropical lakes. *Global Biogeochemical Cycles*, *23*, GB4022. https://doi.org/10.1029/2008GB003434

Pokrovsky, O. S., Shirokova, L. S., Kirpotin, S. N., Kulizhsky, S. P., & Vorobiev, S. N. (2013). Impact of western Siberia heat wave 2012 on greenhouse gases and trace metal concentration in thaw lakes of discontinuous permafrost zone. *Biogeosciences*, *10*(8), 5349–5365. https://doi.org/10.5194/bg-10-5349-2013

Read, J. S., Hamilton, D. P., Desai, A. R., Rose, K. C., MacIntyre, S., Lenters, J. D., … Wu, C. H. (2012). Lake-size dependency of wind shear and convection as controls on gas exchange. *Geophysical Research Letters*, *39*, L09405. https://doi.org/10.1029/2012GL051886

Seekell, D. A., Carr, J. A., Gudasz, C., & Karlsson, J. (2014). Upscaling carbon dioxide emissions from lakes. *Geophysical Research Letters*, *41*, 7555–7559. https://doi.org/10.1002/2014GL061824

Seekell, D. A., Pace, M. L., Tranvik, L. J., & Verpoorter, C. (2013). A fractal-based approach to lake size-distributions. *Geophysical Research Letters*, *40*, 1–5. https://doi.org/10.1002/grl.50139.1

Thienemann, A. (1926). Die Binnengewässer Mitteleuropas.

Tranvik, L. J., Downing, J. A., Cotner, J. B., Loiselle, S. A., Striegl, R. G., Ballatore, T. J., … Weyhenmeyer, G. A. (2009). Lakes and reservoirs as regulators of carbon cycling and climate. *Limnology and Oceanography*, *54*, 2298–2314. https://doi.org/10.4319/lo.2009.54.6_part_2.2298

Vachon, D., Prairie, Y. T., & Cole, J. J. (2010). The relationship between near-surface turbulence and gas transfer velocity in freshwater systems and its implications for floating chamber measurements of gas exchange. *Limnology and Oceanography*, *55*, 1723–1732. https://doi.org/10.4319/lo.2010.55.4.1723

Vachon, D., Prairie, Y. T., & Smith, R. (2013). The ecosystem size and shape dependence of gas transfer velocity versus wind speed relationships in lakes. *Canadian Journal of Fisheries and Aquatic Sciences*, *70*(12), 1757–1764. https://doi.org/10.1139/cjfas-2013-0241

Verpoorter, C., Kutser, T., Seekell, D. A., & Tranvik, L. J. (2014). A global inventory of lakes based on high-resolution satellite imagery. *Geophysical Research Letters*, *41*, 6396–6402. https://doi.org/10.1002/2014GL060641

Wanninkhof, R. (1992). Relationship between wind speed and gas exchange. *Journal of Geophysical Research*, *97*(C5), 7373–7382. https://doi.org/10.1029/92JC00188