LETTERS
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Large contribution to inland water CO_2 and CH_4 emissions from very small ponds

Meredith A. Holgerson* and Peter A. Raymond

Inland waters are an important component of the global carbon cycle. Although they contribute to greenhouse gas emissions[1–5], estimates of carbon processing in these waters are uncertain. The global extent of very small ponds, with surface areas of less than 0.001 km^2, is particularly difficult to map, resulting in their exclusion from greenhouse gas budget estimates. Here we combine estimates of the lake and pond global size distribution, gas exchange rates, and measurements of carbon dioxide and methane concentrations from 427 lakes and ponds ranging in surface area from 2.5 m^2 to 674 km^2. We estimate that non-running inland waters release 0.583 Pg C yr^{-1}. Very small ponds comprise 8.6% of lakes and ponds by area globally, but account for 15.1% of CO_2 emissions and 40.6% of diffusive CH_4 emissions. In terms of CO_2 equivalence, the ratio of CO_2 to CH_4 flux increases with surface area, from about 1.5 in very small ponds to about 19 in large lakes. The high fluxes from very small ponds probably result from shallow waters, high sediment and edge to water volume ratios, and frequent mixing. These attributes increase CO_2 and CH_4 supersaturation in the water and limit efficient methane oxidation. We conclude that very small ponds represent an important inland water carbon flux.

Inland waters actively transform carbon and play an important role in natural and anthropogenic greenhouse gas budgets, including carbon dioxide (CO_2) and methane (CH_4; refs 1–5). Yet, accurately estimating inland water carbon budgets remains challenging. Quantifying carbon flux from inland waters requires estimates of surface water concentrations, the global size distribution of water bodies, and gas transfer velocity (k_{600}), all of which are prone to error[2].

The global size distribution of lakes and ponds is a critical source of uncertainty for calculating gas exchange. Although the global extent of lakes and ponds has interested scientists for centuries[6], the past decade has brought advances in modelling, Geographic Information Systems (GIS), and satellite technology that vastly improve our ability to estimate their size distribution[2,7–11]. A recent analysis using high-resolution satellite imagery estimates that lakes comprise 5.4 million km^2 of surface area, or approximately 3.6% of the earth's land surface[11]. Improved estimates of lake surface area along with a growing number of studies on gas concentration and k_{600} in inland waters lends itself to analysis and upscaling.

So far, upscaling estimates for carbon budgets exclude very small ponds less than 0.001 km^2 in surface area because of uncertainty in their global distribution[2]. Very small ponds cannot be detected on maps or traditional satellite images and can form a continuum with wetlands, making the two difficult to distinguish and leading to ambiguous definitions[6,7]. However, considering that small ponds tend to have higher concentrations of both CO_2 (refs 2,12,13) and CH_4 (refs 13–16) than larger lakes, this size cutoff could underestimate greenhouse gas emissions from inland waters.

In this study, we compiled direct measurements of CO_2 and/or CH_4 concentrations from 427 lakes and ponds globally that ranged in size from 2.5 m^2 to 674 km^2 (Supplementary Table 1). We used concentrations and gas exchange rates to estimate diffusive gas flux from each water body, and estimates of the global size distribution of lakes and ponds to upscale to global carbon efflux and evaluate the importance of very small ponds.

We found that CO_2 and CH_4 concentrations were greatest in small ponds and decreased with increasing lake size (Fig. 1). Models were improved when latitude was used as a covariate (Table 1 and Fig. 1). Surface area and latitude collectively explained 36% and 58% of the variance in CO_2 and CH_4 concentrations, respectively (Table 1). The negative relationship between surface area and CO_2 and CH_4 concentrations may be due to the changing physical properties of lakes and ponds along a size gradient. Small ponds have a high perimeter to surface area ratio and shallow waters, meaning they receive higher loads of terrestrial carbon relative to water volume. Terrestrial carbon provides substrate for microbial respiration, which can increase CO_2 concentrations[17]. In addition, sediment respiration, which often follows anoxic pathways, can affect the entire water column of shallow, well-mixed ponds[12], increasing CO_2 concentrations, decreasing oxygen, and supporting CH_4 production[13–16]. Finally for CH_4, shallow depths and frequent mixing mean more rapid exchange with the atmosphere and less time for CH_4 removal by oxidation[18]. These factors promote greater concentrations of CO_2 and CH_4 in small ponds compared to larger lakes.

Small ponds are also more variable in gas concentrations than larger lakes (Table 2). This variability is probably because factors influencing gas concentrations, such as canopy cover, depth, and dissolved organic carbon (DOC; refs 16,19), vary more in smaller systems. For instance, CO_2 and CH_4 saturation in small northern-latitude ponds depends on the presence of cyanobacteria mats (reduces CO_2; ref. 19) and thermokarst (increases CO_2 and CH_4; ref. 20). Accounting for these differences will be important, particularly as permafrost regions warm, creating more thaw ponds, and potentially increasing greenhouse gas emissions.

The relationship between CO_2 concentration and latitude was quadratic, where mid-latitude (50°–60°) lakes had the highest CO_2 concentrations. This finding contrasts previous work indicating that tropical and boreal lakes had higher CO_2 concentrations than mid-latitude lakes[3]. Our results may indicate that other variables, such as DOC, are more important than latitude and temperature in driving respiration and CO_2 concentrations[17]. The relationship between CH_4 and latitude was linear,

School of Forestry and Environmental Studies, Yale University, New Haven, Connecticut 06511, USA. *e-mail: meredith.holgerson@gmail.com

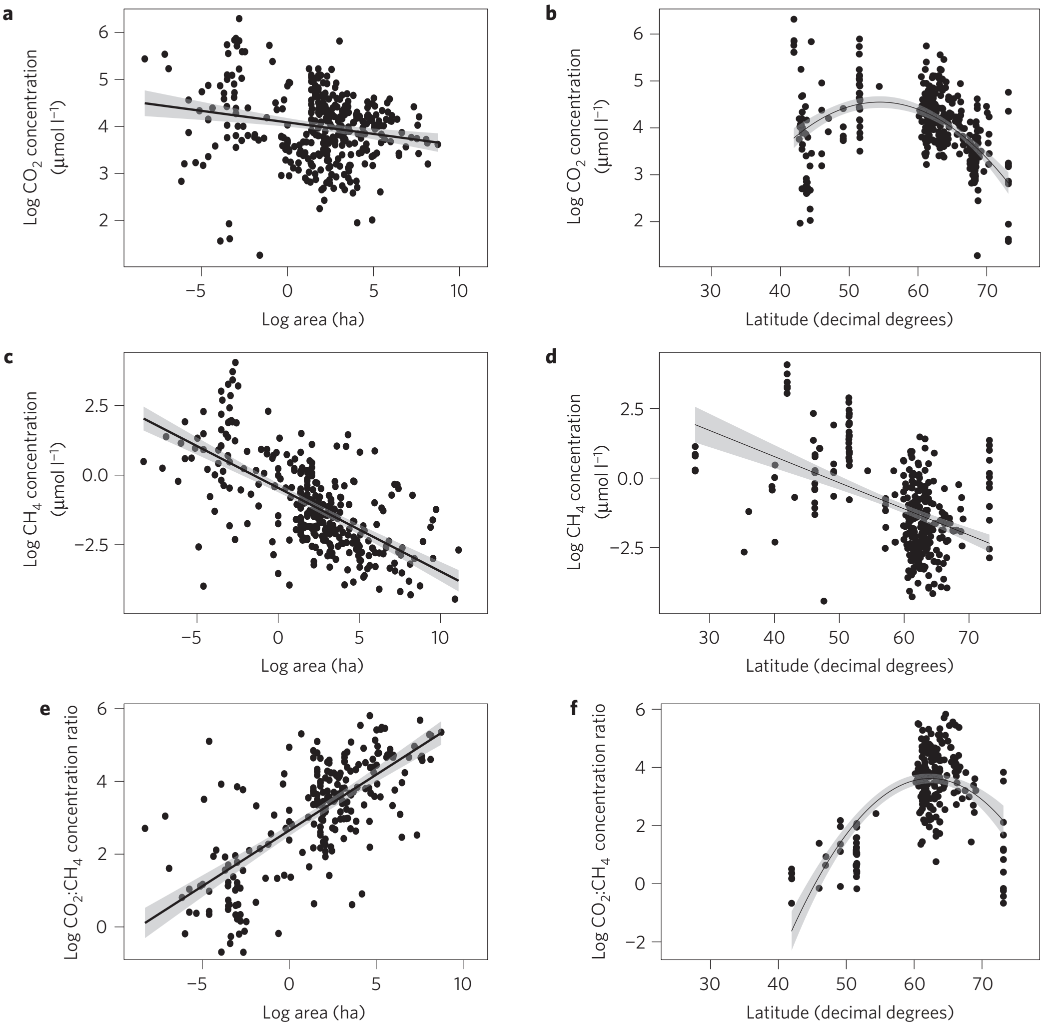

Figure 1 | CO_2 and CH_4 concentrations in relation to lake surface area and latitude. a,**c**,**e**, Relationships between surface area and CO_2 concentration, CH_4 concentration, or their ratio, respectively. **b**,**d**,**f**, Relationships between latitude and CO_2 concentration, CH_4 concentration, or their ratio, respectively. The ratio between CO_2 and CH_4 is in carbon dioxide equivalents. Log transformations are natural log. DF, degrees of freedom.

Table 1 | Relationship between gas concentrations, lake or pond surface area and latitude.

Equation	Intercept	Area (ln)	Latitude	Latitude$_a^2$	Area (ln) × Latitude$_a$	*F*	*p*	R^2
$\ln(CO_2) \sim \ln(\text{area}) \times \text{latitude}_a$	4.44	−0.061	−0.055	−0.0042	0.008	49.1	<0.001	0.36
$+ \text{latitude}_a^2$	(0.06)	(0.011)	(0.005)	(0.0005)	(0.0014)	(4, 343 DF)		
$\ln(CH_4) \sim \ln(\text{area}) + \text{latitude}$	4.25	−0.278	−0.080	-	-	213.2	<0.001	0.58
	(0.440)	(0.017)	(0.007)	-	-	(2, 306 DF)		
Ratio ($\ln CO_2/\ln CH_4$) ~	5.20	0.190	0.063	−0.0081	0.0077	109.2	<0.001	0.65
$\ln(\text{area}) \times \text{latitude}_a + \text{latitude}_a^2$	(0.090)	(0.022)	(0.012)	(0.0011)	(0.0034)	(4, 225 DF)		

Latitude$_a$: values are centred around the mean.

where temperate lakes and ponds had higher CH_4 concentrations than those in boreal systems, which is consistent with other studies[21].

Interestingly, the ratio of CO_2 to CH_4 concentration increased with lake size (Fig. 1 and Table 2). In terms of CO_2 equivalence, CO_2 concentrations were only ten times greater than CH_4 in the smallest ponds, but were 150 times higher in large lakes (Table 2). This CO_2 to CH_4 concentration ratio is probably driven by surface area and its correlate, lake depth. Methane is produced in anoxic sediments and waters, and can be oxidized by oxygen in the water column. This potential for CH_4 oxidation is higher in deeper lakes with longer residence times, and is less for shallow waters[18]. As such, the surface waters of stratified lakes tend to have lower CH_4 concentrations[13], but may experience increased CH_4 flux following lake turnover[22].

To upscale to global efflux estimates, we grouped ponds and lakes into seven logarithmic size classes (Table 2), which helps to minimize variance and reduce bias[2]. We used established literature values of the gas transfer velocity (k_{600}), which increases with lake size (Table 1), along with water temperature to convert

Table 2 | Characteristics of surface area, gas exchange rates, and gas concentrations and fluxes for each lake size class.

Size class (km^2)	Surface area (km^2)	k_{600}	CO_2			CH_4			Ratio CO_2:CH_4				
			n	Conc. (μmol l^{-1})	Flux (mmol C m^{-2} d^{-1})	*n*	Conc. (μmol l^{-1})	Flux (mmol C m^{-2} d^{-1})	*n*	Conc.	Conc. (CO_{2eq})	Flux	Flux (CO_{2eq})
<0.001	147,763 861,578	0.36	50	133.99 (16.69)	35.18 (5.21)	50	7.57 (1.64)	2.28 (0.51)	50	92.22 (33.21)	10.12 (3.64)	15.46	1.70
0.001–0.01	406,575.9	0.48	22	70.29 (14.8)	21.21 (5.88)	20	1.70 (0.49)	0.65 (0.16)	14	157.42 (48.99)	17.28 (5.38)	32.49	3.57
0.01–0.1	675,233.8	0.57	111	68.79 (4.4)	21.57 (1.85)	86	0.68 (0.09)	0.28 (0.05)	60	399.14 (49.66)	43.81 (5.45)	77.13	8.46
0.1–1	984,650.6	0.80	110	58.05 (4.1)	23.87 (3.03)	86	0.36 (0.07)	0.16 (0.04)	63	483.46 (50.96)	53.06 (5.59)	151.68	16.65
1–10	782,073.8	0.85	45	57.83 (3.3)	22.42 (1.88)	43	0.24 (0.08)	0.12 (0.06)	33	968.53 (124.73)	106.30 (13.69)	192.50	21.13
10–100	597,789.3	1.09	10	47.27 (5.7)	20.90 (4.08)	18	0.20 (0.06)	0.10 (0.05)	10	1,361.34 (233.10)	149.41 (25.58)	204.21	22.41
>100	2,024,015.8	1.15	1	32.63	11.49	6	0.13 (0.04)	0.06 (0.04)	0	-	-	-	-

Concentration ratios are calculated for each lake; flux ratios are averages for the size class. Numbers in parentheses represent standard error.

concentration to flux for each lake. We then took the gas flux for each lake size class and the size distribution of lakes (Table 2) to upscale to global flux. Because gas concentrations vary within each lake size class, we used a Monte Carlo analysis to randomly and iteratively select a gas concentration from a normal distribution around the mean.

As there are no direct measurements for the global size distribution of very small ponds <0.001 km^2, we addressed this uncertainty using a Monte Carlo analysis to randomly and iteratively select a size distribution from a uniform distribution between a lower and an upper bound. The lower bound was extrapolated from a linear regression on the number of lakes in the three lowest size classes available from high-resolution satellite images[11], yielding a global estimate of 5.47×10^8 ponds. The upper bound used the Pareto distribution to produce a global estimate of 3.2×10^9 ponds[23]. We then used a mean surface area of 0.00027 km^2 to estimate that ponds in this smallest size class comprise a global surface area between 147,763 and 861,578 km^2.

We estimate that lakes and ponds emit 0.583 Pg C yr^{-1} (25–75th percentiles: 0.452–0.696 Pg C yr^{-1}). Of the total efflux, 0.571 Pg C yr^{-1} (25–75th percentiles: 0.439–0.683 Pg C yr^{-1}) comes from CO_2 and 0.012 Pg C yr^{-1} (25–75th percentiles: 0.006–0.015 Pg C yr^{-1}) comes from CH_4 diffusive flux (Fig. 2 and Supplementary Information 1.2). Notably, ponds from the smallest size class (<0.001 km^2) have a disproportionately large contribution to carbon flux relative to their size. We estimate that very small ponds make up only 8.6% (25–75th percentiles: 5.9–11.2%) of the global surface area of lakes and ponds, yet comprise 15.1% (25–75th percentiles: 4.5–23.1%) of all CO_2 emissions and 40.6% (25th–75th percentiles: 0–68.8%) of all diffusive CH_4 emissions from lentic freshwaters (Fig. 2).

Our estimate of CO_2 flux is higher than the most recent estimate of 0.3 Pg C yr^{-1} of CO_2 emitted from lakes and ponds globally, which used a lower estimate of lake surface area and excluded very small ponds[2], and our estimate is on par with earlier estimates of 0.5–0.6 Pg C yr^{-1} that also omitted very small ponds[3,4]. For CH_4, our estimate is on par with a previous estimate of 0.0097 Pg C yr^{-1} from CH_4 diffusive flux from global lakes[21], but higher than estimates from The Global Carbon Project[24].

The ratio of CO_2 to CH_4 flux increases with lake size (Fig. 2c), which is driven by the large diffusive CH_4 flux from small ponds. In terms of CO_2 equivalence, global CO_2 flux is only 1.5 times higher than global CH_4 flux in very small ponds, but is 19 times greater in the largest lakes (Fig. 2c). Although this study focused on diffusive CH_4 fluxes, CH_4 ebullition from lakes and ponds can be significant and larger than diffusive flux[21], particularly in shallow ponds[14,18], thermokarst ponds[20], and along lake edges[18]. We did not incorporate ebullition in our estimates because few studies measure ebullition and it is not well predicted from surface area (Supplementary Information 2.3); yet, if ebullition is included, small ponds would probably be responsible for an even greater proportion of CH_4 fluxes than reported here.

The contribution of very small ponds (<0.001 km^2) to total carbon efflux incorporates uncertainty in both gas concentration and surface area. Despite this added uncertainty, the coefficient of variation was similar among all size classes (Supplementary Information 1.2 and 1.3). Within each of the upper size classes, variation in gas concentration was greater than variation in surface area estimates, and this appears true for very small ponds as well. More direct measurements of CO_2 and CH_4 concentration and flux are needed from inland waters of all sizes. Despite current uncertainty, because very small ponds comprise ~15.1% and ~40.6% of global CO_2 and CH_4 emissions from lentic inland waters, respectively, their inclusion in flux estimates may be critical to quantifying natural carbon budgets, particularly at the regional scale.

A better understanding of the global size distribution of very small ponds will reduce uncertainty surrounding inland water greenhouse gas emissions. The number of small ponds is often modelled from the Pareto distribution, which typically fits the regional distributions of lakes in flat landscapes[10] and some boreal landscapes down to a threshold pond size of 30–400 m^2 (ref. 25). In those regions, excluding small ponds from the carbon budget could largely overestimate terrestrial net ecosystem productivity, as small ponds respire significant amounts of terrestrial carbon[26]. However, the Pareto distribution may overestimate the number of small ponds in other regions[9,10]. For instance, in the Northern Highland Lake District, where lakes have been mapped down to 0.0001 km^2, the number of small ponds falls in the mid-range of our surface area estimates[27]. Yet even in regions where the size distribution of small ponds deviates from the Pareto distribution, very small ponds dominate numerically, and their exclusion in carbon budgets may introduce bias at the regional and global scale[27]. Clearly, more research on the global distribution of small ponds is needed for upscaling, which will require

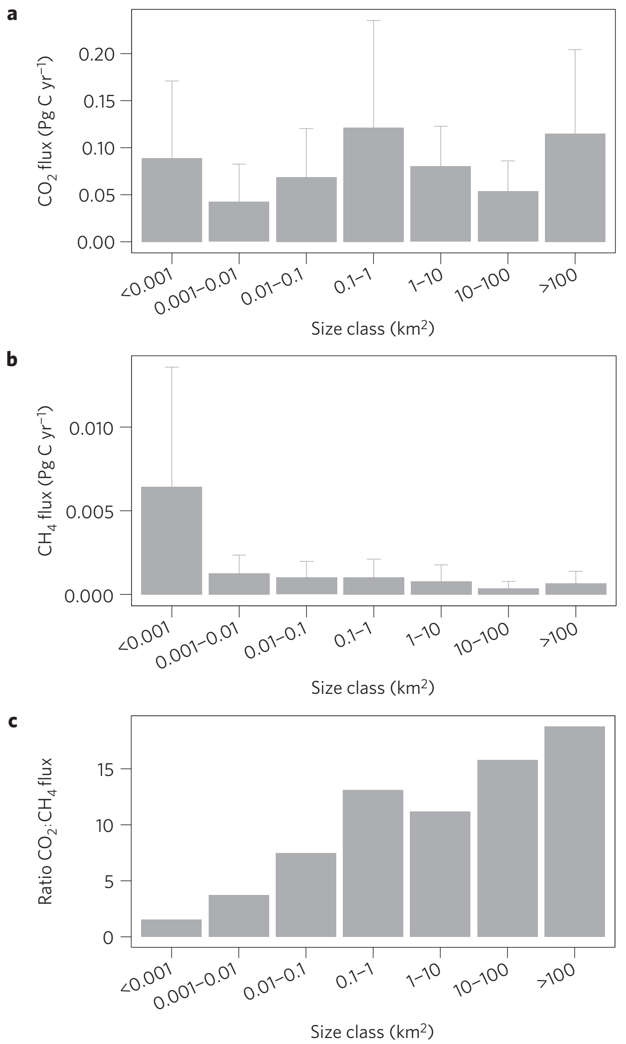

Figure 2 | Estimated global flux of CO_2 and CH_4 for each lake size class. **a**–**c**, Estimates are shown for CO_2 flux (+s.d.) (**a**), diffusive CH_4 flux (+s.d.) (**b**), and the ratio between CO_2 and diffusive CH_4 flux (**c**) (in CO_2 equivalence).

capitalizing on new technologies to map small ponds. Several small-scale studies have successfully used light-detection and ranging (LiDAR) data[28], real-colour aerial images[29], leaf-off colour-infrared aerial images[30], or a combination of these techniques[28] to map very small ponds. By expanding these small-scale estimates to global coverage, we will more accurately quantify carbon flux from inland waters.

Overall, our study provides the first global estimate of CO_2 and diffusive CH_4 efflux from ponds $<0.001\,km^2$. We demonstrate that very small ponds can have exceptionally high CO_2 and CH_4 concentrations, which are apparently sufficient to compensate for lowered gas exchange velocities. These small ponds make a substantial contribution to diffusive CH_4 flux from inland waters, and have a smaller but still important role in CO_2 flux. It is clear that very small ponds, which comprise the majority of lakes and ponds by number[8,23], play a critical role in geochemical cycling and represent an important contribution to natural carbon cycling in inland waters.

Methods

Methods and any associated references are available in the online version of the paper.

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Author contributions

M.A.H. and P.A.R. conceived and designed the analysis. M.A.H. compiled all data, performed data analysis, and wrote most of the manuscript. P.A.R. aided in data interpretation and helped to write the manuscript.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to M.A.H.

Competing financial interests

The authors declare no competing financial interests.

Methods

Data acquisition. We conducted literature searches using keywords including 'CO_2', 'CH_4', 'carbon dioxide' and 'methane' with 'concentration' and either 'lake' or 'pond' using Google Scholar and Web of Science in September 2014. We then searched the reference section of relevant papers for additional studies. We also included our own data set on small, temperate ponds published after we conducted our literature search (ref. 16).

We included ponds and lakes only where CO_2 or CH_4 concentrations were measured directly (that is, headspace equilibration methods) because CH_4 cannot be indirectly measured and CO_2 calculated from temperature, pH and alkalinity can be grossly overestimated, particularly in waters with high DOC and low pH (ref. 31), common of small ponds[16]. We included only water bodies where CO_2 or CH_4 concentration, surface area and latitude were reported or made available from authors. We did not include reservoirs, because emissions fluctuate with reservoir age and gas pathways in the dam[32,33]. Floodplain lakes were excluded because they are often included in lotic water flux estimates[34] and it is difficult to separate lentic versus lotic fluxes and dynamics. We excluded saline or brackish lakes owing to their unique biogeochemistry and paucity of direct measurements[35]. Last, we excluded ponds and lakes that were reported to be mostly vegetated, because emergent vegetation takes up CO_2 and reduces gas exchange, altering flux dynamics[1]. When the same water body was reported in multiple studies, we used the study that reported the greatest number of sampling dates, either across seasons or years. In total, we compiled direct measurements of CO_2 and/or CH_4 from 427 lakes and ponds globally (Supplementary Table 1).

Estimating annual gas concentrations. The majority of lakes and ponds (281 of 427) were sampled multiple times across the year; for these sites, we calculated the average concentration over the open-water period. The exception is for Finnish lakes, where we used seasonally weighted averages described for lakes in that region[12]. To scale up to annual fluxes, we assumed the average concentration was representative of the entire year. For the 34% of sites where gas concentrations were taken only once (usually in the middle of the open-water season), this assumption may underestimate concentrations. In large lakes with seasonal stratification, surface CO_2 and CH_4 concentrations are highest immediately after ice-off and lowest during the summer, when lakes stratify and photosynthesis is high[36], indicating mid-summer snapshots may underestimate annual averages. In very small ponds, however, seasonal trends do not seem to be as strong[16], perhaps due to polymictic and/or strongly net heterotrophic conditions. Our estimates do not discount for periods of the year where a pond or lake may be ice covered. When a lake is ice covered, there is generally a build up of CO_2 and CH_4 under the ice that greatly increases efflux during spring melt[12,15,37,38]. However, gas concentrations may not build up if the pond or lake freezes completely or if the pond or lake is oligotrophic[14], which we could not account for. We also did not discount for the possibility that some smaller ponds may dry seasonally. There is recent evidence that dry pond[39], peatland[40], and stream[41] beds release high fluxes of carbon, a phenomenon that would reward further study.

Estimating gas flux for each water body. We estimated gas flux from concentration for each pond or lake using water temperature, gas exchange velocity (k_{600}), and atmospheric CO_2 or CH_4 concentrations. We used water temperatures at the time of sampling when available; however, water temperature was not reported for 31 sites. For these cases, we used average air temperatures for the study region and study time and converted them to water temperature using an established relationship[2]: water temperature $=$ air temperature $\times$ 0.67 $+$ 7.45; $R^2 = 0.65$, $p < 0.001$. We used atmospheric CO_2 and CH_4 concentrations for each year by taking a seasonal average (May through September) from monthly averages reported from flask measurements at Mauna Loa, Hawaii, USA. One lake (Lake Mendota, Wisconsin, USA) was sampled in 1977 before Mauna Loa CH_4 concentrations were available. For this lake, we used CH_4 concentrations estimated from Antarctic ice cores[42].

We classified each pond or lake into seven logarithmic bin classes and used estimates of k_{600} for each size class to estimate gas flux (Table 2). For lakes $>0.01\ km^2$, we used k_{600} values from Raymond *et al.*[2] because they provide an intermediate estimate between conservative wind-speed derived values[43] and potentially overestimated values derived from the relationship with lake area[44]. For ponds 0.001–0.01 km^2 (below the size cutoff for Raymond *et al.*[2]), we used the lake area-k_{600} relationship described by Read and colleagues[44]. This method may overestimate k_{600} because estimates were derived from measurements taken at the lake's centre, which is often less sheltered than the edges[2]. However, this is less of a concern for small ponds, as conditions at the pond centre are more similar to the edges. For ponds $<0.001\ km^2$, we used the average k_{600} from four study ponds located in northeastern Connecticut, USA that we measured using a propane gas tracer in 2013 (M. Holgerson, E. Farr, and P. Raymond, unpublished data). For discussion on the assumptions of our k_{600} estimates, see Supplementary Information 2.1.

Our data set of direct measurements of CO_2 and CH_4 concentrations had no lakes in the largest size class ($>100\ km^2$) for CO_2 concentrations. As a surrogate, we used a concentration of 659 µatm, which was the mean estimate from indirect measurements (calculated from pH, alkalinity, and temperature) reported by Raymond and colleagues[2]. We assumed the seasonal average temperature to be 12.76 °C, the average reported for the lakes in our data set, and used a k_{600} of 1.15 $m\ d^{-1}$ to estimate gas flux to be 11.49 $mmol\ C\ m^{-2}\ d^{-1}$. Indirect measurements correlate well with direct measurements in lakes that have a circumneutral pH and low DOC (ref. 31), common in very large lakes. However, three available direct measurements of CO_2 flux for lakes $>100\ km^2$ demonstrated a net negative flux, indicating that lakes studied were undersaturated with CO_2 (ref. 45), and that our flux estimate could be overestimated. Future studies should directly measure CO_2 in large lakes, particularly because their large surface area and high k_{600} could introduce large error into global estimates of carbon flux.

Upscaling to global carbon flux. We upscaled CO_2 and CH_4 diffusive flux at the lake scale to the global scale with a Monte Carlo analysis that ran 1,000 iterations for each size class. Each iteration randomly selected a CO_2 and CH_4 concentration based on a normal distribution surrounding the mean and standard deviation for that size class (see Statistical analysis below). We then multiplied the gas concentration by the total global area of lakes or ponds in that size class, as determined by the most recent inventory on the global size distribution of lakes[11] (Table 2). This global inventory used high-resolution satellite images to identify and provide morphometry on all global lakes $>0.002\ km^2$. For lakes $<0.002\ km^2$, we estimated lake size distribution as follows. For lakes within the 0.001 to 0.01 km^2 size class, we assumed that lakes between 0.001 and 0.002 km^2 comprised 10% of lakes in the entire size class, which equalled 9,988,889 lakes. This may be slightly conservative as Verpoorter *et al.*[11] used 0.004 km^2 as the mean lake size in this size class. We then multiplied the number of lakes by the estimated mean of the size class (0.004 km^2) to determine the surface area of lakes between 0.001 and 0.002 km^2 to be 40,000 km^2.

There are no agreed on estimates for the global size distribution of lakes in the smallest size class (0.0001–0.001 km^2); therefore, we incorporated this uncertainty in our Monte Carlo analysis by using a lower and an upper bound estimate. The number of lakes in the lower bound estimate was extrapolated from the three smallest size classes (between 0.001 and 1 km^2) from the high-resolution satellite images described above[11]. Using a log–log linear regression, we estimated there to be 547,268,724 lakes between 0.0001 and 0.001 km^2 (linear regression, number of lakes (ln) $= -0.7115879163^{\times}$ size class $+ 8.7382006294$, $R^2 = 0.996$). Our upper bound is based on the Pareto distribution, which estimates that there are 3.19×10^9 ponds in this size class[23]. The number of lakes for both the lower and upper bound was then multiplied by the estimated mean size of lakes in the size class, which we calculated to be 0.00027 km^2 according to Equation 8 in Downing and colleagues[8]. For discussion on the uncertainty of the global size distribution of very small ponds, see Supplementary Information 2.2.

Statistical analysis. We performed linear regressions to evaluate the relationship between CO_2 and CH_4 concentrations with area. We used latitude as a covariate, as gas concentrations and flux can be affected by latitude[3,12,46]. We evaluated interactions, linear and quadratic relationships, and selectively removed non-significant variables. The relationship between the natural log of CO_2 and latitude was quadratic, and as such we centred values around the mean to meet assumptions of collinearity. We compared CO_2 and diffusive CH_4 flux from the different lake size classes using analysis of variance (ANOVA).

To estimate global carbon efflux from lakes and ponds, we used a Monte Carlo uncertainty analysis. This analysis incorporated uncertainty in gas flux by selecting from a normal distribution from the mean and standard deviation gas flux in that size class (Supplementary Information 2.1). If the number selected was less than zero (owing to high standard error), the flux was forced to zero. The Monte Carlo analysis ran 1,000 simulations. All analyses were done using R (R Version 3.1.2, R Core Team).

Data sources. The compiled data on the 427 lakes and ponds can be found in Supplementary Table 1. The complete list of references can be found in the Supplementary Information 4 document.

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Corrigendum: Large contribution to inland water CO_2 and CH_4 emissions from very small ponds

Meredith A. Holgerson and Peter A. Raymond

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In the original version of this Letter published online, the scale of the *x* axis in panels a, c and e in Fig. 1 did not extend over the full data range, and as a result three data points were omitted from each panel. In addition, all instances of 'Supplementary Methods' and 'Supplementary References' have been changed to 'Supplementary Information'. This has been corrected in all versions of the Letter.