Seasonal and diel variation in greenhouse gas emissions from an urban pond and its major drivers

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Abstract

Small water systems are important hotspots of greenhouse gas (GHG) emission, but estimates are poorly constrained as data are scarce. Small ponds are often constructed in urban areas, where they receive large amounts of nutrients and therefore tend to be highly productive. Here, we investigated GHG emissions, seasonal and diel variation, and net ecosystem production (NEP) from an urban pond. In monthly 24-h field campaigns during 11 months, diffusive water–atmosphere methane (CH4) and carbon dioxide (CO2) fluxes and CH4 ebullition and oxidation were quantified. With oxygen (O2) measurements, NEP was assessed. The pond was a net GHG source the entire year, with an emission of 3.4 kg CO2 eq m−2 yr−1. The dominant GHG emission pathway was CH4 ebullition (bubble flux, 50%), followed by diffusive emissions of CO2 (38%) and CH4 (12%). Sediment CH4 release was primarily driven by temperature and especially ebullition increased exponentially above a temperature threshold of 15°C. The pond’s atmospheric CO2 exchange was not related to NEP or temperature but likely to a high allochthonous carbon (C) input via runoff and anaerobic mineralization of C. We expect urban ponds to show a large increase in GHG emission with increasing temperature, which should be considered carefully when constructing ponds in urban areas. Emissions may partly be counteracted by pond management focusing on a reduction of nutrient and organic matter input.

Although lakes and ponds only cover a small area of the Earth’s nonglaciated land area (~4%; Verpoorter et al. 2014), they play a disproportionally large role in the global carbon cycle due to the large amount of C they process, store, and transport (Tranvik et al. 2009). The majority of lakes and ponds is a significant source of CO2 and CH4 to the atmosphere (Cole et al. 1994; Bastviken et al. 2011), while at the same time, they bury large amounts of C in their sediments (Dean and Gorham 1998; Mendonça et al. 2017). Carbon emission in lakes and ponds is largely driven by hydrological CO2 inputs (Weyhenmeyer et al. 2015; Wilkinson et al. 2016) and by mineralization of organic matter (OM) within the system (Algesten et al. 2003). Conversely, primary producers can assimilate CO2 at such high rates that the system turns into a CO2 sink (Roland et al. 2010; Pacheco et al. 2013). However, global and regional studies suggest that only a small portion of lakes (6–14%) is undersaturated with respect to the atmospheric CO2 (Cole et al. 1994; Kosten et al. 2010).

Annually, lentic inland waters emit 0.3 Pg C as CO2 (Raymond et al. 2013) and 0.08 Pg C as CH4 (Bastviken et al. 2011). This last value may be an underestimate, as ebullition is likely underestimated (Wik et al. 2016). Although small waterbodies (< 50 ha) comprise 98% of lentic inland waters by number and one third by volume (Downing et al. 2006; Verpoorter et al. 2014), small lakes and ponds are strongly underrepresented in literature (Downing 2010), and greenhouse gas emission in lakes and ponds is largely driven by hydrological CO2 inputs (Weyhenmeyer et al. 2015; Wilkinson et al. 2016) and by mineralization of organic matter (OM) within the system (Algesten et al. 2003). Conversely, primary producers can assimilate CO2 at such high rates that the system turns into a CO2 sink (Roland et al. 2010; Pacheco et al. 2013). However, global and regional studies suggest that only a small portion of lakes (6–14%) is undersaturated with respect to the atmospheric CO2 (Cole et al. 1994; Kosten et al. 2010).

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and nighttime field measurements on a monthly basis with laboratory assays and modeling.

We hypothesized the pond to be an important GHG emitter as well as an important C sink, with a higher CH4 emission during warm months. We further hypothesized that the pond would shift between a net C source in fall and winter to a net C sink in spring and summer, mainly due to fluctuations in CO2 emission caused by phytoplankton growth—i.e., high CO2 uptake by photosynthesis in summer and much less so in winter. Because of the high primary production, we also expected a high variability in diel CO2 emission, especially in summer. Due to the shallowness of the pond (average depth of 1.3 m), we expected the sediment to be a major contributor to CO2 emission but simultaneously an important site for C burial because of a high OM loading.

**Materials and methods**

In the field, we measured diffusive water–atmosphere fluxes of CH4 and CO2, ebullitive CH4 fluxes, water layer CH4 oxidation rates, and diel oxygen (O2) concentrations. The pond’s net ecosystem production (NEP), GPP, and ER were calculated from O2 concentrations. A metabolic model was constructed that included aerobic respiration estimates for each organism group (organisms in the sediment, phytoplankton, heterotrophic picoplankton, and fish), based on temperature and O2 consumption. The outcome of both the field and laboratory measurements, combined with data from an existing hydrological model for the pond area, and literature data, were joined in a mass balance to unravel the major contributors to the CO2 flux. Finally, C burial rates in the pond were determined in order to compare C burial and emission rates.

**Study site and sampling strategy**

This study was performed in manmade urban pond situated in Malden, Gelderland, the Netherlands ("Korte Loëf," 51°46′30″N, 5°51′11.22″E). The pond was constructed in 1994 to function as a rainwater overflow for the surrounding urban area. It covers an area of 4635 m², stores approximately 6000 m³ of water, and has distinct central (±2 m) and littoral (±1 m) zones (respectively, 44% and 56% of the total surface area). Monthly field campaigns were performed from July 2013 till May 2014. During the field campaigns, measurements were performed over 24-h periods at two sampling stations, one in the central and one in the littoral zone, that were placed at the same location every field campaign. Groundwater samples were taken from a well situated 20 m from the shore. Every 15 min, the O2 concentration, temperature, and pH were measured. Diffusive gas fluxes were measured every 3 h during the campaign, whereas methane ebullition and oxidation were measured separately in the light and dark period. We did not sample in June due to logistic reasons, therefore values for this month were interpolated using the average values of May and July in order to obtain year-round estimates. Areal estimates of gas fluxes for the entire pond were calculated based on the
weighted average of the central and littoral area. In our analyses, we considered the months June, July, and August as the summer season; September, October, and November as fall; December, January, and February as winter; and March, April, and May as spring.

**Water chemistry**

A depth integrated water sample was taken from each of the sampling stations once per field campaign for chemical analyses. Unfiltered water samples were analyzed for total phosphorus (TP), by inductively coupled plasma spectrometry (ICP-OES iCAP 6000, Thermo Fisher Scientific), and for total inorganic nitrogen (TIN) by measuring and summing the ammonium (NH₄⁺) and nitrate (NO₃⁻) concentrations. Ammonium and nitrate were measured colorimetrically with an Auto Analyzer 3 system (Bran & Luebbe), using salicylate (Grasshoff and Johannsen 1972) and hydrazine sulfate (Kamphake et al. 1967), respectively. Phytoplankton chlorophyll-α (Chl a) concentration and division over major groups (brown, green, and blue Chl a) were determined using a phytoplankton analyzer system with a portable emitter-detector unit (Phyto-PAM and Phyto-ED, Walz).

**O₂, temperature, and pH**

During the monthly 24-h field campaigns, we deployed a multiparameter portable meter (HQ40d, Hach) equipped with a luminescent/optical dissolved oxygen probe (LDO101) fitted with a temperature and barometric pressure sensor (model LDO101) and a pH-temperature sensor (model 9156BNWP) at the littoral and at the central station, at 0.5 m depth. Dissolved O₂ concentration, temperature, pH, and barometric pressure were recorded every 15 min. A third multimeter was used to sample vertical dissolved O₂ and temperature profiles at both stations every 3 h.

**CO₂ and CH₄ emission**

Diffusive CO₂ and CH₄ fluxes across the air–water interface were measured using a transparent Plexiglas floating chamber (30 cm diameter, 20 cm height) connected to a GHG analyzer (GGA) using Off-axis ICOS technology (GGA-24r-EP, Los Gatos Research). A closed loop between the chamber and the detector was established using an inlet and outlet on the top of the chamber. A third opening, fitted with an air-tight screw cap, was used to equilibrate the chamber with atmospheric pressure prior to each measurement. Measurements were conducted every 3 h, by placing the chamber three times (treated as triplicates) at the central and littoral zone. Each measurement took about 200 s, and the GGA was configured to log data every second. The flux of CO₂ and CH₄ was calculated based on the slope of the relationship between the concentration in the chamber headspace and time:

\[ F = \frac{(V/A) \times \text{slope} \times ([P \times F1 \times F2])}{(R \times T)} \]

where \( F \) is the gas flux (g m⁻² d⁻¹), \( V \) is the chamber volume (m³), \( A \) is the chamber surface area (m²), slope is the slope of the relationship between the CH₄ or CO₂ concentration and the time (ppm s⁻¹), \( P \) is atmospheric pressure (Pa), \( F1 \) is molar mass of CO₂ (44) or CH₄ (16) (g mole⁻¹), \( F2 \) is the conversion factor of seconds to days, \( R \) is gas constant 8.3145 (m³ Pa K⁻¹ mol⁻¹), and \( T \) is temperature (K). The values from the replicate measurements were averaged to give the flux of each station (i.e., central or littoral zone). The fluxes of CO₂ and CH₄ were multiplied by their global warming potential (GWP, 1 and 34 over a 100 yr time horizon, respectively; Myhre et al. 2013) and then summed to obtain the total GHG flux in CO₂ equivalents (CO₂ eq).

**Ebullition**

In order to quantify the spontaneous release of bubbles from sediments to the atmosphere (ebullition), three inverted funnels with a diameter of 35 cm were connected to water-filled infusion bottles (volume of 0.5 liter) and employed at the pelagic zone of the pond (as in Almeida et al. [2016]). Infusion bottles were replaced at sunset or sundown, and after collection, the gas volume was measured by subtracting the weight of each bottle from the full filled weight (i.e., completely filled with water) of the bottle. The CH₄ concentration of the gas was analyzed on a HP 5890 gas chromatographe equipped with a Porapak Q column (80/100 mesh) and a flame ionization detector (GC-FID, Hewlett Packard).

**CH₄ oxidation and sediment CH₄ release**

CH₄ oxidation was measured as the decline in CH₄ concentration over time (as in Bastviken et al. [2008]), in three flexible medical blood bags (volume 500 mL) located in the shallow (0.5 m) or deep (1 or 2 m, depending on whether it was the littoral or central zone, respectively) part of the water column, in each sampling station. Separate blood bags were incubated with pond water from the corresponding depth, during day and night to evaluate potential temporal differences in CH₄ oxidation. The exact same procedure was followed as in Almeida et al. (2016). As a proxy for sediment CH₄ release, we used the sum of quantified CH₄ oxidation, CH₄ water-atmosphere diffusion, and CH₄ ebullition. In months where no CH₄ oxidation was quantified due to technical difficulties (January and May), oxidation was estimated as a function of the diffusive CH₄ flux. The rationale behind this is that the methane oxidation rate strongly depends on the methane concentration, which, in turn, affects CH₄ diffusion (CH₄ oxidation = 0.0476 × exp [28.97 × CH₄ diffusion]; \( R^2_{adj} = 0.87 \)).

**NEP and respiration by different organism groups**

We used 15-min interval O₂ measurements to calculate the O₂ change over time (ΔO₂; g O₂ L⁻¹ h⁻¹) and subsequently calculated NEP by integrating ΔO₂ over 24 h (as in Cole et al. [2000] and Staehr et al. [2010]). From the NEP, GPP, and ER were calculated (see Supporting Information SI 1 for details). Subsequently, we distinguished different organism groups.
contributing to the aerobic ER in the pond: phytoplankton, heterotrophic picoplankton, and methanotrophs in the water layer; organisms in the sediment; and fish. To assess the contribution of all separate organism groups to the ER, we constructed a metabolic model consisting of the relationship between water temperature and O₂ consumption for each organism group. These relationships were based on incubations and—for fish respiration—on literature-derived relationships (see Supporting Information SI 2 for details).

Hydrological inputs and within-pond CO₂ production
For each season, we assessed the relative importance of hydrological CO₂ input via groundwater, within-pond CO₂ production from ecosystem productivity (NEP) and from photochemical mineralization of chromophoric dissolved organic carbon (cDOC) (see Supporting Information SI 3 for details). The CO₂ input from groundwater was calculated based on the estimated groundwater inflow and the CO₂ concentration in the groundwater. Photochemical mineralization cDOC was calculated as a direct response to solar radiation exposure and solely based on the average daily light intensity (as in Vähätalo et al. [2000] and Weyhenmeyer et al. [2015]). Light intensity data were obtained from weather station Volkel, Noord-Brabant, The Netherlands.

C burial
Organic C burial rates were estimated by taking six sediment cores (6 cm diameter) with a piston sampler at locations distributed over the central zone of the pond, determining total C content and dividing the estimated areal C stock of the pond by its age (according to Mendonça et al. [2014]; see Supporting Information SI 4 for details).

Statistics
All statistical analyses were performed using R (version 3.5.0). Statistical significance was determined at \( p < 0.05 \). The effect of location (littoral or center) and time of day (day or night) on GHG fluxes and methane oxidation were tested using linear mixed-effects and generalized linear mixed-effects models (LMM and GLMM, respectively) using the “lme4” package (Bates et al. 2015; see Supporting Information SI 5 for details). For methane oxidation, the effect of water depth (shallow or deep) was also evaluated. Assumptions of linearity, homoscedasticity, and normality were checked by visual inspection of residual plots and a Shapiro Wilk’s test (function shapiro.test), respectively (see Supporting Information SI 5 for details). Simple linear regression and nonlinear regression were performed using the lm and nls function, respectively. Coefficients and \( p \) values for Pearson correlations were obtained using the rcorr function (“Hmisc” package). All error values in the manuscript give the standard deviation.

Results
Water chemistry
The yearly average concentrations of TP and TIN were 4.5 ± 0.9 and 54.0 ± 32.3 μmol L⁻¹, respectively. The average Chl \( \alpha \) concentration was 81 ± 29 μg L⁻¹, with the lowest concentration observed in April (37 μg L⁻¹) and highest concentration in July (119 μg L⁻¹). The water layer was dominated by cyanobacteria during summer and fall and by green algae during winter and spring. The observed water temperature varied from 4.3°C during winter to 27.8°C during summer and was 13.0°C ± 0.7°C on average. The O₂ concentration, measured at 0.5 m depth, varied between 1.6 and 13.5 mg L⁻¹ during the year and was on average 9.1 ± 2.6 mg L⁻¹. The O₂ concentration near the bottom of the pond ranged between approximately 0 and 11 mg L⁻¹. During July, August, and September, diurnal stratification occurred, with mixing occurring at night. During the other months, the pond was homogeneously mixed all day. The pH had a neutral value on average (7.2 ± 0.2), with slightly acidic values in summer (pH around 6.5) and slightly basic values in spring and fall (pH around 8).

Carbon flux and burial
The urban pond was a net C source all year with an average C (CO₂-C and CH₄-C) emission of 1.07 ± 0.43 g C m⁻² d⁻¹. On average, the diffusive CO₂ emission was 0.95 ± 0.40 g CO₂-C m⁻² d⁻¹, with the highest values measured in summer and winter season (Figs. 1, 3). CO₂ diffusion was not related to temperature \((F_{1,9} = 0.204; p = 0.66, R^2 = 0.02)\) or Chl \( \alpha \) concentration \((F_{1,9} = 0.008; p = 0.93, R^2 = 0.001)\). Both diffusive and ebullitive CH₄ emission were positively related to temperature \((R_{2 adj}^2 = 0.86\) and \(R_{2 adj}^2 = 0.82\), respectively) and thus similarly the total CH₄ emission as a sum of these fluxes was positively related to temperature (Fig. 2). The diffusive and ebullitive CH₄ emission were, respectively, 0.02 ± 0.30 and 0.10 ± 0.49 g CH₄-C m⁻² d⁻¹. Most CH₄ was emitted via the ebullitive emission pathway (75%), and only approximately 25% was emitted via diffusion. When taking the GWP into account, we found a yearly GHG emission (CO₂ and CH₄ emission combined) of 9.19 ± 7.99 g CO₂ eq m⁻² d⁻¹. The yearly average ebullitive CH₄ emission was 4.63 ± 6.70 g CO₂ eq m⁻² d⁻¹, which was considerably higher than the other fluxes. The yearly average diffusive CO₂ and CH₄ emissions were respectively 3.46 ± 1.48 and 1.09 ± 4.09 g CO₂ eq m⁻² d⁻¹. An annual average C burial rate of 29 g C m⁻² yr⁻¹ was found, which is substantially lower than the annual C emission (CO₂ and CH₄ emission combined) of 391 g C m⁻² yr⁻¹.

Sediment CH₄ release and CH₄ oxidation
The sediment CH₄ release was estimated by summing the average CH₄ diffusion, ebullition, and oxidation in the water column for each month. The estimated sediment CH₄ release was positively related to water temperature \((T_w)\), with the highest release rate observed at the highest water temperature (Fig. 2). There seems to be a threshold around 15°C, above which the sediment CH₄ release increases substantially (from April up to and including September). The estimated sediment CH₄ release varied considerably throughout the year, from 0.01 ± 0.005 g CH₄-C m⁻² d⁻¹ in March to 1.04 ± 0.46 g CH₄-C m⁻² d⁻¹ in July (Fig. 2). The percentage of estimated sediment CH₄ emission that was oxidized
before reaching the atmosphere, varied from 0% to 97% over the year (average 57%), with values ranging between 0 and 0.58 g CH$_4$-C m$^{-2}$ d$^{-1}$. On average, 0.16 g CH$_4$-C m$^{-2}$ d$^{-1}$ was oxidized. We found a significant location-depth interaction effect (GLMM: Wald $Z = 6.31; p < 0.001$): the effect of deep vs. shallow incubation on CH$_4$ oxidation rates is larger for the littoral than the central zone of the pond. There was also a significant time-location-depth interaction (GLMM: Wald $Z = -15.59; p < 0.001$).

Temporal and spatial variation in C fluxes

The CO$_2$ : CH$_4$ emission ratio (in CO$_2$ equivalents) varied strongly over the year (Supporting Information Table S2). In March, the ratio was 1 and there was an equal share of GHG emitted. From April until September, the ratio was well below 1, indicating the importance of CH$_4$ emission. The ebullitive CH$_4$ flux dominated the GHG emission, with a share of 75% of total CH$_4$ emission and 50% of total GHG emission. From October until February, CO$_2$ formed the majority of GHG emission, with a share of 80% to 96%. The CH$_4$ emissions were low during these coldest months (< 0.5 g CO$_2$ eq m$^{-2}$ d$^{-1}$), and more than 85% of methane released by the sediment was oxidized (Fig. 3). No significant temporal (LMM: $F_{1,10} = 2.87; p = 0.12$) and spatial (LMM: $F_{1,10} = 4.09; p = 0.07$) difference in diffusive CO$_2$ flux was found. Similarly, there was no significant temporal (LMM: $F_{1,10} = 3.01; p = 0.11$) nor spatial (LMM: $F_{1,10} = 2.61; p = 0.14$) difference in diffusive CH$_4$ emission, although the emission was mostly higher in the central zone (Supporting Information Fig. S1). For ebullition, we found a significant main effect of location (GLMM: Wald $t = 2.18; p = 0.029$), with higher ebullition in the center of the pond. In addition, we found a significant

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Fig. 1. Measured CO$_2$ diffusion, CH$_4$ diffusion, and CH$_4$ ebullition in CO$_2$ equivalents (g CO$_2$ eq m$^{-2}$ d$^{-1}$) ± SD. At some dates, the error bars (SD) are too small to show in the figure.

Fig. 2. Relationship between water temperature and CH$_4$ fluxes in the pond. All average values are shown with their standard deviation, but at some dates, the error bars are too small to show. The solid line shows the relationship of water temperature with the average total CH$_4$ emission to the atmosphere (black dots), which includes water–atmosphere diffusion and ebullition. The dashed line shows the relationship of water temperature with sediment CH$_4$ release (white dots), which was calculated as the sum of water–atmosphere CH$_4$ diffusion and ebullition and water column CH$_4$ oxidation. Note that CH$_4$ oxidation rates were not measured in January and May. In these months, we estimated CH$_4$ oxidation rates based on the relationship between CH$_4$ diffusion and oxidation (see Materials and Methods section).

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interaction (GLMM: Wald $t = 2.66$; $p = 0.008$) between time and location: the effect of the center vs. the littoral zone of the pond was higher for nighttime than for daytime CH$_4$ ebullition rates.

Relative importance of hydrological inputs and within-pond CO$_2$ production

High GPP rates were found throughout the year (average of $3.30 \pm 2.79$ g CO$_2$-C m$^{-2}$ d$^{-1}$); however, high rates of ER were observed as well ($3.66 \pm 2.66$ g CO$_2$-C m$^{-2}$ d$^{-1}$). On average, ER rates exceeded GPP rates, which led to net heterotrophy in the system (average NEP of $-0.36 \pm 0.69$ g CO$_2$-C m$^{-2}$ d$^{-1}$). We found net heterotrophy in the system in 8 out of 11 months (NEP of $-0.64 \pm 0.48$ g CO$_2$-C m$^{-2}$ d$^{-1}$) and (minor) net autotrophy in the months February, March, and September (with a respective NEP of 0.02, 0.30, and 1.08 g CO$_2$-C m$^{-2}$ d$^{-1}$). In months where ER exceeded GPP, the contribution of the NEP to the measured CO$_2$ emission from the pond was approximately 50% on average. In months with net autotrophy (GPP > ER), the pond still emitted CO$_2$. When CO$_2$ inputs from groundwater (yearly average of $0.03 \pm 0.01$ g C m$^{-2}$ d$^{-1}$) and CO$_2$ formed by photochemical mineralization of DOC (yearly average of $0.009 \pm 0.007$ g C m$^{-2}$ d$^{-1}$) were added to the NEP in months with net heterotrophy (indicating CO$_2$ production), the contribution to the measured CO$_2$ emission was 56%.

Partitioning of ER between organism groups

Empirical relations found to predict organism group-specific respiration (Supporting Information Table S1), based on the relationship between temperature and respiration rates, failed to accurately predict the measured ER of the system (based on the nighttime O$_2$ decrease at 50 cm depth; Supporting Information Fig. S2). The sum of the modeled respiration of the different organism groups only accounted for roughly half (56%) of the aerobic ER, estimated from the nighttime O$_2$ curve (Supporting Information Fig. S3). Phytoplankton respiration contributed most to the modeled aerobic ER, with 34.7% on average. After that, the heterotrophic picoplankton and sediment organisms in the lake contributed most to ER with 26.8% and 24.3%, respectively. Fish and methanotrophs contributed the least to ER, with 8.9% and 5.3%, respectively.

Discussion

Our findings demonstrate that the temperate urban pond was a year-round source of GHG, with a particularly large CH$_4$ emission. The areal GHG emitted by the pond was 3.4 kg CO$_2$ eq m$^{-2}$ yr$^{-1}$, which corresponds to 15.5 t of CO$_2$ equivalents emitted from the pond surface per year. CH$_4$ ebullition was by far the most important GHG emission pathway (~50% of total emission), especially during warm months as we hypothesized (> 15°C, mostly in spring and summer), while
Diffusive CH$_4$ and CO$_2$ emission contributed with 12% and 38%, respectively. The diffusive CH$_4$ emission from this small urban pond was three times higher than the average emission reported for small waterbodies within the same size class (on average 0.01 g CH$_4$ m$^{-2}$ d$^{-1}$, size class 0.001–0.01 km$^2$; Holgerson and Raymond 2016). Moreover, the total CH$_4$ emission (168 mg CH$_4$ m$^{-2}$ d$^{-1}$) is moderately high compared to other temperate lakes, irrespective of lake size (Supporting Information Table S3). The OC burial rate corresponded to approximately 6% of the total C emission from the pond (443 g C m$^{-2}$ yr$^{-1}$), which is rather low, as a recent global analyses indicate that on average lakes and reservoir C burial corresponds to roughly 20% of their emissions (Mendonça et al. 2017). Opposed to our hypothesis, the pond did not shift between a net C source in fall and winter to a net C sink in spring and summer. The pond emitted CO$_2$ to the atmosphere throughout the entire year, even in months where diel oxygen curves indicated the pond was net autotrophic, suggesting that external CO$_2$ sources other than within-system aerobic respiration play an important role. Overall, the urban pond acted as a “carbon hub,” receiving carbon from different sources, processing, and redirecting the carbon in different ways.

Sediment CH$_4$ release was strongly related to water temperature and increased exponentially above 15°C (Fig. 2), mainly due to increased ebullition. This result corroborates findings in other systems in various climate regions where temperature-induced exponential increases in ebullition were observed (Aben et al. 2017). Nutrients and organic C limitation may constrain sediment CH$_4$ release and thereby impede its increase with warming (Kelly and Chynoweth 1981; Schwarz et al. 2008; DelSontro et al. 2016). This is, however, unlikely to occur in hypertrophic urban ponds, where labile OM availability tends to be high throughout the year both due to internal production and external inflow. The high OM availability and anoxic conditions in pond sediments, combined with the shallow water layer, readily explain the high rates of CH$_4$ ebullition in our pond (Sobek et al. 2012; Martinez-Cruz et al. 2017). As these conditions are common in urban ponds (Waajen et al. 2014), our results imply that CH$_4$ emission from these systems is high and strongly temperature dependent. The increase of CH$_4$ oxidation with rising temperature was much weaker than that of sediment CH$_4$ release, which resulted in a high summer CH$_4$ emission (Fig. 2) and is in accordance with a previous laboratory study (Sepulveda-Jauregui et al. 2018). In fall and winter, a high proportion (over 85%) of CH$_4$ was oxidized (Fig. 3) and emissions were low. CH$_4$ oxidation rates in our pond were comparable with rates found in other eutrophic systems, which were in a range between 0 and 0.32 g C m$^{-2}$ d$^{-1}$ (Bastviken 2009). Only during July—when water temperature was the highest recorded (25°C)—we found a rate exceeding the reported range (0.58 g C m$^{-2}$ d$^{-1}$). Notably, our estimates do not incorporate oxidation at the sediment–water interface, which can be considerable (Bastviken 2009; Martinez-Cruz et al. 2018).

Diffusive CO$_2$ emission was, after CH$_4$ ebullition, the most important contributor to the pond’s total GHG emission. The internally produced CO$_2$ (NEP), calculated based on diel O$_2$ curves, was always lower than the measured CO$_2$ emission rates (comprising on average ~ 50% of the emission rate). Even during phytoplankton blooms in summer, when GPP exceeded ER, CO$_2$ was emitted to the atmosphere (6.1 ± 3.5 g CO$_2$-C m$^{-2}$ d$^{-1}$). Daytime an nighttime CO$_2$ emissions were not statistically different. This indicates that the pond’s atmospheric CO$_2$ exchange was not strongly regulated by primary production within the lake, opposed to our hypothesis and to findings of Pacheco et al. (2013). CO$_2$ input from groundwater and photochemical mineralization of DOC was responsible for approximately 6% of the measured CO$_2$ emission. The unexplained fraction of the CO$_2$ emission likely originates from endogenous anaerobic CO$_2$ production or exogenously produced CO$_2$ (entering via runoff or local groundwater originating from e.g., leaves from trees, street dirt, or bird droppings). Endogenous anaerobic CO$_2$ may arise from denitrification, which seems likely as Dutch groundwater often contains a large amount of nitrate (Smolders et al. 2006). Allochthonous C is known to drive CO$_2$ emission in small and shallow ponds, owing to their high perimeter to volume ratio (Finlay et al. 2010; Holgerson 2015; Wilkinson et al. 2016). Other possible factors that may explain the discrepancy between the measured CO$_2$ emission and estimated internal CO$_2$ production include inaccurate estimates of oxygen saturation and gas transfer velocity, as well as a possible underestimation of daytime respiration (Del Giorgio and Williams 2005; Staehr et al. 2010; Brothers et al. 2017). Estimating respiration rates per organism group is a difficult practice as well and comes with several uncertainties and caveats (Del Giorgio and Williams 2005; Martínez-García et al. 2013), which was confirmed by the fact that our modeled ER only accounted for roughly half of the oxygen diel-curve–derived ER.

Seasonal trends in GHG emissions from temperate ponds have generally been disregarded based on the observation that GHG emissions in these systems are often not primarily driven by the seasonally varying within-system metabolism (Jonsson et al. 2003; Holgerson 2015). Although in our pond NEP played a minor role in driving C emission as well, we did find a clear seasonal pattern in GHG emissions (Figs. 1, 3). This seasonal trend is strongly determined by ebullition (Fig. 1; Supporting Information Table S2). We found a lower CO$_2$ : CH$_4$ emission ratio with increasing temperature (Supporting Information Table S2), largely due to an increase in CH$_4$ emission, in accordance with other studies (Yvon-Durocher et al. 2014; DelSontro et al. 2016). Unexpectedly, we did not find clear differences in spatial and temporal (daytime or nighttime) diffusive GHG emission. Both, CH$_4$ ebullition and diffusion were, however, clearly related to temperature and ebullition was significantly higher in the central zone of the pond. The latter contradicts other studies that suggest the littoral zone plays a more important role in GHG emissions (Natchimuthu et al. 2016). Because of the high spatiotemporal variation in total GHG emission and the high importance of CH$_4$
We recommend future studies to explicitly incorporate ebullition measurements and to take spatial differences into account even in small systems, such as ponds. Furthermore, future monitoring efforts in comparable temperate and eutrophic systems should be concentrated in the months May through September, as in these months the highest fluxes and highest variation occurs. A low number of measurements in fall and winter can be used to estimate cold season emissions.

Extrapolating our findings to all urban ponds in the Netherlands (extrapolated from data by Waajen et al. [2014]), we find a GHG emission of 0.27 Mt CO₂ eq yr⁻¹. This equals the annual emission of approximately 193,000 cars (based on driving 13,200 km yr⁻¹). City planners consider ponds as natural cooling mechanisms to mitigate urban heat stress (Inard et al. 2004; Theeuwes et al. 2013); however, our findings indicate that this is not a GHG neutral option. In addition, hypereutrophic urban ponds are more likely to be affected by raising temperatures, as water temperatures of small and shallow systems are closely correlated to air temperature, making them sensitive to rapid warming (Toffolon et al. 2014; Wik et al. 2014). Shallow, urban ponds with a high OM input may thus likely exhibit enhanced CH₄ emissions with global warming induced rising of water temperatures (O’Reilly et al. 2015). Considering their already high GHG emission rates, their inclusion in regional GHG emission assessments is important. Climate change will likely feedback on urban ponds GHG emissions and additionally worsen eutrophication and OM loading to the system (Moss et al. 2011). In line with the idea of using local management strategies to mitigate global stressors (Scheffer et al. 2015), management strategies for urban ponds should be aimed at reducing eutrophication and OM loading. In this way, local management may counteract the warming induced increase of GHG emissions as well.

References

Aben, R. C., and others. 2017. Cross continental increase in methan emission under climate change. Nat. Commun. 8: 1682. doi:10.1038/s41467-017-01535-y

Algesten, G., S. Sobek, A. K. Bergström, A. Ågren, L. J. Tranvik, and M. Jansson. 2003. Role of lakes for organic carbon cycling in the boreal zone. Glob. Chang. Biol. 10: 141–147. doi:10.1046/j.1529-8817.2003.00721.x

Almeida, R. M., and others. 2016. High primary production contrasts with intense carbon emission in a eutrophic tropical reservoir. Front. Microbiol. 7: 717. doi:10.3389/fmicb.2016.00717

Balmer, M. B., and J. A. Downing. 2011. Carbon dioxide concentrations in eutrophic lakes: Undersaturation implies atmospheric uptake. Inland Waters 1: 125–132. doi:10.5268/IW-1.2.366

Bastviken, D. 2009. Methane. In G. E. Likens [ed.], Encyclopedia of inland waters. Elsevier.
northern Great Plains. Limnol. Oceanogr. **55**: 1551–1564. doi:10.4319/lo.2010.55.4.1551

Gledhill, D. G., P. James, and D. H. Davies. 2008. Pond density as a determinant of aquatic species richness in an urban landscape. Landsc. Ecol. **23**: 1219–1230. doi:10.1007/s10980-008-9292-x

Grashoff, K., and H. Johannsen. 1972. A new sensitive and direct method for the automatic determination of ammonia in sea water. ICES J. Mar. Sci. **34**: 516–521. doi:10.1093/icesjms/34.3.516

Hanson, P. C., S. R. Carpenter, J. A. Cardille, M. T. Coe, and L. A. Winslow. 2007. Small lakes dominate a random sample of regional lake characteristics. Freshwater Biol. **52**: 814–822. doi:10.1111/j.1365-2427.2007.01730.x

Holgerson, M. A. 2015. Drivers of carbon dioxide and methane supersaturation in small, temporary ponds. Biogeochemistry **124**: 305–318. doi:10.1007/s10533-015-0099-y

Holgerson, M. A., and P. A. Raymond. 2016. Large contribution to inland water CO2 and CH4 emissions from very small ponds. Nat. Geosci. **9**: 222–226. doi:10.1038/NGEO2654

Inard, C., D. Groleau, and M. Musy. 2004. Energy balance study of water ponds and its influence on building energy consumption. Build. Serv. Eng. Res. Technol. **25**: 171–182. doi:10.1191/0143624404bt1060a

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

Kamphake, L., S. Hannah, and J. Cohen. 1967. Automated analysis for nitrate by hydrazine reduction. Water Res. **1**: 205–216. doi:10.1016/0043-1354(67)90011-5

Kelly, C. A., and D. P. Chynoweth. 1981. The contributions of temperature and of the input of organic matter in controlling rates of sediment methanogenesis. Limnol. Oceanogr. **26**: 891–897. doi:10.4319/lo.1981.26.5.0891

Kosten, S., F. Roland, D. M. L. Da Motta Marques, E. H. Van Nes, N. M. L. d. S. L. Sternberg, M. Scheffer, and J. J. Cole. 2010. Climate-dependent CO2 emissions from lakes. Global Biogeochem. Cycles **24**: 24. doi:10.1029/2009GB003618

Martinez-Cruz, K., R. Gonzalez-Valencia, A. Sepulveda-Jauregui, F. Plascencia-Hernandez, Y. Belmonte-Izquierdo, and F. Thalasso. 2017. Methane emission from aquatic ecosystems of Mexico City. Aquat. Sci. **79**: 159–169. doi:10.1007/s00207-016-0487-y

Martinez-Cruz, K., A. Sepulveda-Jauregui, P. Casper, K. W. Anthony, K. A. Smemo, and F. Thalasso. 2018. Ubiquitous and significant anaerobic oxidation of methane in freshwater lake sediments. Water Res. **144**: 332–340. doi:10.1016/j.watres.2018.07.053

Martinez-García, S., E. Fernández, D. A. del Valle, D. M. Karl, and E. Teira. 2013. Experimental assessment of marine bacterial respiration. Aquat. Microb. Ecol. **70**: 189–205. doi:10.3354/ame01644

Mendonça, R., S. Kosten, S. Sobek, J. J. Cole, A. C. Bastos, A. L. Albuquerque, S. J. Cardoso, and F. Roland. 2014. Carbon sequestration in a large hydroelectric reservoir: An integrative seismic approach. Ecosystems **17**: 430–441. doi:10.1007/s10021-013-9735-3

Mendonça, R., R. A. Müller, D. Clow, C. Verpoorter, P. Raymond, L. J. Tranvik, and S. Sobek. 2017. Organic carbon burial in global lakes and reservoirs. Nat. Commun. **8**: 1694. doi:10.1038/s41467-017-01789-6

Moss, B., and others. 2011. Allied attack: Climate change and eutrophication. Inland Waters **1**: 101–105. doi:10.5268/IW-1.2.359

Myhre, G., and others. 2013. Anthropogenic and natural radiative forcing, p. 659–740. In T. F. Stocker et al. [eds.], Climate change 2013: The physical science basis. Contribution of Working Group I to the fifth assessment report of the intergovernmental panel on climate change. Cambridge Univ. press.

Natchimuthu, S., I. Sundgren, M. Gälfalk, L. Klemmedtsson, P. Crill, Å. Danielsson, and D. Bastviken. 2016. Spatio-temporal variability of lake CH4 fluxes and its influence on annual whole lake emission estimates. Limnol. Oceanogr. **61**: S13–S26. doi:10.1002/ino.10222

Novotny, V. 1999. Integrating diffuse-nonpoint pollution control and water body restoration into watershed management. J. Am. Water Resour. Assoc. **35**: 717–727. doi:10.1111/j.1752-1688.1999.tb04169.x

O’Reilly, C. M., and others. 2015. Rapid and highly variable warming of lake surface waters around the globe. Geophys. Res. Lett. **42**: 10,773–710,781. doi:10.1002/2015GL066235

Pacheco, F. S., F. Roland, and J. A. Downing. 2013. Eutrophication reverses whole-lake carbon budgets. Inland Waters **4**: 41–48. doi:10.5268/IW-4.1.614

Raymond, P. A., and others. 2013. Global carbon dioxide emissions from inland waters. Nature **503**: 355–387. doi:10.1038/nature12760

Roland, F., L. O. Vidal, F. S. Pacheco, N. O. Barros, A. Assireu, J. P. H. B. Ometto, A. C. P. Cumbris, and J. J. Cole. 2010. Variability of carbon dioxide flux from tropical (Cerrado) hydroelectric reservoirs. Aquat. Sci. **72**: 283–293. doi:10.1007/s00207-010-0140-0

Sand-Jensen, K., and P. A. Stæhr. 2009. Net heterotrophy in small Danish lakes: A widespread feature over gradients in trophic status and land cover. Ecosystems **12**: 336–348. doi:10.1007/s10021-008-9226-0

Scheffer, M., and others. 2015. Creating a safe operating space for iconic ecosystems. Science **347**: 1317–1319. doi:10.1126/science.aaa3769

Scherer, N. M., H. L. Gibbons, K. B. Stoops, and M. Muller. 1995. Phosphorus loading of an urban lake by bird droppings. Lake Reservoir Manage. **11**: 317–327. doi:10.1080/07438149509354213

Schwarz, J. I., W. Eckert, and R. Conrad. 2008. Response of the methanogenic microbial community of a profound Lake
sedi-ment (Lake Kinneret, Israel) to algal deposition. Limnol.
Oceano-ogr. 53: 113–121. doi:10.4319/o.2008.53.1.0113
Sepulveda-Jauregui, A., J. Hoyos-Santillan, K. Martinez-Cruz,
K. M. Walter Anthony, P. Casper, Y. Belmonte-Izquierdo, and
F. Thalasso. 2018. Eutrophication exacerbates the impact of
climate warming on lake methane emission. Sci. Total Envi-
ron. 636: 411–419. doi:10.1016/j.scitotenv.2018.04.283
Smith, V. H. 1979. Nutrient dependence of primary produc-
tivity in lakes. Limnol. Oceanogr. 24: 1051–1064. doi:
10.4319/lo.1979.24.6.1051
Smolders, A., L. Lamers, E. Lucassen, G. Van der Velde, and
J. Roelofs. 2006. Internal eutrophication: How it works and
what to do about it—a review. Chem. Ecol. 22: 93–111.
doi:10.1080/02757540600579730
Sobek, S., T. DelSontro, N. Wongfun, and B. Wehrli. 2012.
Extreme organic carbon burial fuels intense methane bubbling
in a temperate reservoir. Geophys. Res. Lett. 39: L01401. doi:
10.1029/2011GL050144
Staehr, P. A., D. Bade, M. C. Van de Bogert, G. R. Koch,
C. Williamson, P. Hanson, J. J. Cole, and T. Kratz. 2010.
Lake metabolism and the die1 oxygen technique: State of the
science. Limnol. Oceanogr.: Methods 8: 628–644. doi:
10.4319/lom.2010.8.628
Theeuwes, N., A. Solcerová, and G. Steeneveld. 2013. Modeling
the influence of open water surfaces on the summertime
temperature and thermal comfort in the city. J. Geophy-
s. Res.: Atmos. 118: 8881–8896. doi:10.1002/jgrd.50704
Toffolon, M., S. Piccolroaz, B. Majone, A.-. M. Soja, F. Peeters,
M. Schmid, and A. Wüst. 2014. Prediction of surface tem-
perature in lakes with different morphology using air
temperature. Limnol. Oceanography 59: 2185–2202. doi:
10.4319/lo.2014.59.6.2185
Tranvik, L. J., and others. 2009. Lakes and reservoirs as regu-
lators of carbon cycling and climate. Limnol. Oceanogr. 54:
2298–2314. doi:10.4319/lo.2009.54.6_part_2.2298
Trolle, D., P. A. Staehr, T. A. Davidson, R. Bjerring, T. L.
Lauridsen, M. Sondergaard, and E. Jeppesen. 2012. Seasonal
dynamics of CO2 flux across the surface of shallow temper-
ate lakes. Ecosystems 15: 336–347. doi:10.1007/s10021-0
11-9513-z
Vähätalo, A. V., M. Salkinoja-Salonen, P. Taalas, and K. Salonen.
2000. Spectrum of the quantum yield for photo-
chemical mineralization of dissolved organic carbon in a
humic lake. Limnol. Oceanogr. 45: 664–676. doi:10.4319/
lo.2000.45.3.0664
Verpoorter, C., T. Kutser, D. A. Seekell, and L. J. Tranvik. 2014.
A global inventory of lakes based on high-resolution satel-
lite imagery. Geophys. Res. Lett. 41: 6396–6402. doi:10.1002/
2014GL060641
Waaijen, G. W., E. J. Faassen, and M. Lürling. 2014. Eutrophic
urban ponds suffer from cyanobacterial blooms: Dutch
examples. Environ. Sci. Pollut. Res. 21: 9983–9994. doi:
10.1007/s11356-014-2948-y

Waschbusch, R. J., W. R. Selbig, and R. T. Bannerman. 1999.
Sources of phosphorus in stormwater and street dirt from
two urban residential basins in Madison, Wisconsin,
1994-95, p. 51. Water-Resources Investigations Report.
West, W. E., J. J. Coloso, and S. E. Jones. 2012. Effects of algal
and terrestrial carbon on methane production rates and
methanogen community structure in a temperate lake
dediment. Freshwater Biol. 57: 949–955. doi:10.1111/j.1
365-2427.2012.02755.x
West, W. E., K. P. Creamer, and S. E. Jones. 2016. Productivity
and depth regulate lake contributions to atmospheric
methane. Limnol. Oceanogr. 61: S51–S61. doi:10.1002/
lo.10247
Weyhenmeyer, G. A., S. Kosten, M. B. Wallin, L. J. Tranvik,
E. Jeppesen, and F. Roland. 2015. Significant fraction of
CO2 emissions from boreal lakes derived from hydrologic
inorganic carbon inputs. Nat. Geosci. 8: 933–936. doi:
10.1038/ngeo2582
Wik, M., B. F. Thornton, D. Bastviken, S. MacIntyre, R. K.
Varner, and P. M. Crill. 2014. Energy input is primary con-
troller of methane bubbling in subarctic lakes. Geophys.
Res. Lett. 41: 555–560. doi:10.1002/2013GL058510
Wik, M., R. K. Varner, K. W. Anthony, S. MacIntyre, and
D. Bastviken. 2016. Climate-sensitive northern lakes and
ponds are critical components of methane release. Nat.
Geosci. 9: 99–105. doi:10.1038/NGEO2578
Wilkinson, G. M., C. D. Buelo, J. J. Cole, and M. L. Pace. 2016.
Exogenously produced CO2 doubles the CO2 efflux from
three north temperate lakes. Geophys. Res. Lett. 43:
1996–2003. doi:10.1002/2016GL067732
Wong, T., P. F. Breen, and S. D. Lloyd. 2000. Water sensitive
road design: Design options for improving stormwater
quality of road runoff. CooperativeCenter for Catchment
Hydrology.
Yvon-Durocher, G., A. P. Allen, D. Bastviken, R. Conrad,
C. Gudasz, A. St-Pierre, N. Thanh-Duc, and P. A. del
Giorgio. 2014. Methane fluxes show consistent temperature
dependence across microbial to ecosystem scales. Nature
507: 488–491. doi:10.1038/nature13164

Acknowledgments
We thank K. F. Ettwig for her advice and discussions. We thank Paul
van de Ven, Germa Verheggen, Stefan Weideveld, Haijung Wang,
Maarten Schimmel, Carlos Henrique Duque Estrada and Felipe Rust for
their assistance during the experiment and for helping with analyses. We
also thank Jan Schaart (HSV Heumen) for providing an estimation of fish
biomass and species in the pond and for logistic support on site. Addi-
tionally, we thank Roel van Veen from water authority Rivierenland for provid-
ing us groundwater seepage estimates and Simone Cardoso for advice on
the statistical analyses. This study was conducted under the auspices of the
CAPES (Brazil)/NUFFIC (The Netherlands), project 004/2008. N.B. was
supported by Coordenação de Aperfeiçoamento de Pessoal de Nível Supe-
rior (CAPES) process number 3934-13-6 and CAPES (Brazil)/NUFFIC (The
Netherlands) project 045/2012; S.K. was supported by NWO-VENI (grant
86312012); and V.H. was partially supported by Conselho Nacional de
Desenvolvimento Científico e Tecnológico (CNPq, Brazil).
Conflict of Interest
None declared

Author Contribution Statement
V.H., M.L., and S.K. initiated the overarching project. N.B., R.M. and S.K. initiated the study present in the paper. N.B., R.M., T.J.H.M.v.B and I.H.J.A. conducted the fieldwork. T.J.H.M.v.B and N.B. analysed the data. I.H.J.A. and N.B. conducted the sediment incubation. R.A. contributed to the statistical analyses. T.J.H.M.v.B. did the majority of the manuscript writing. T.J.H.M.v.B., N.B., R.M., R.A., I.H.J.A., V.H., L.P.M.L., M.L., F.R. and S.K. contributed to revisions of the manuscript.

Submitted 29 July 2018
Revised 31 January 2019
Accepted 14 March 2019

Associate editor: Kimberly Wickland