Comparing methane ebullition variability across space and time in a Brazilian reservoir

Annika Linkhorst 1,*, Carolin Hiller 1,† Tonya DelSontro 2, Guilherme M. Azevedo 3, Nathan Barros 3, Raquel Mendonça 3, Sebastian Sobek 1

1 Limnology, Department of Ecology and Genetics, Uppsala University, Uppsala, Sweden
2 Aquatic Physics Group, Faculty of Science, Department F.-A. Forel for Environmental and Aquatic Sciences, University of Geneva, Geneva, Switzerland
3 Department of Biology, Institute of Biological Sciences, Federal University of Juiz de Fora, Juiz de Fora, Brazil

Abstract

The potent greenhouse gas methane (CH$_4$) is readily emitted from tropical reservoirs, often via ebullition (bubbles). This highly stochastic emission pathway varies in space and time, however, hampering efforts to accurately assess total CH$_4$ emissions from water bodies. We systematically studied both the spatial and temporal scales of ebullition variability in a river inflow bay of a tropical Brazilian reservoir. We conducted multiple highly resolved spatial surveys of CH$_4$ ebullition using a hydroacoustic approach supplemented with bubble traps over a 12-month and a 2-week timescale to evaluate which scale of variation was more important. To quantify the spatial and temporal variability of CH$_4$ ebullition, we used the quartile coefficients of dispersion at each point in space and time and compared their frequency distributions across the various temporal and spatial scales. We found that CH$_4$ ebullition varied more temporally than spatially and that the intra-annual variability was stronger than daily variability within 2 weeks. We also found that CH$_4$ ebullition was positively related to water temperature increase and pressure decrease, but no consistent relationship with water column depth or sediment characteristics was found, further highlighting that temporal drivers of emissions were stronger than spatial drivers. Annual estimates of CH$_4$ ebullition from our study area may vary by 75–174% if ebullition is not resolved in time and space, but at a minimum we recommend conducting spatially resolved measurements at least once during each major hydrologic season in tropical regions (i.e., in dry and rainy season when water levels are falling and rising, respectively).

Inland waters have been recognized as relevant carbon sources to the atmosphere (Cole et al. 2007; Tranvik et al. 2009; DelSontro et al. 2018; Drake et al. 2018) and integrated into the greenhouse gas budget of the Intergovernmental Panel on Climate Change (IPCC 2013) report. It has been suggested that the impoundment of rivers may increase emission due to flooding of terrestrial organic matter, and additionally through accumulation of sediment containing degradable organic material (St. Louis et al. 2000; Prairie et al. 2018). Tropical reservoirs, in particular, have been indicated as strong sources of the powerful greenhouse gas methane (CH$_4$; Barros et al. 2011) because these warmer regions of the earth are rich in biomass (St. Louis et al. 2000). As greenhouse gas emission from reservoirs can be highly variable across space and time (Abril et al. 2005; DelSontro et al. 2011; Maeck et al. 2013; Maeck et al. 2014; Musenze et al. 2014; Paranaiba et al. 2018), it is difficult to upscale from single measurements at discrete sampling occasions or locations to a whole-system flux estimate. EBullition (bubbling), often, although not always, the dominant CH$_4$ emission pathway from reservoirs (Deemer et al. 2016), has been described as stochastic with high variability in space and time (DelSontro et al. 2011, 2015) and is especially difficult to representatively measure for system-wide estimates. Consequently, ebullition has often been excluded from CH$_4$ emission studies (Deemer et al. 2016) not only leading to underestimation of CH$_4$ emissions from reservoirs, but also to a substantial lack of knowledge regarding the spatiotemporal variability of CH$_4$ ebullition in reservoirs.

Previous studies have shown that lake or reservoir CH$_4$ ebullition can peak at certain points in space (“hot spots”) or time (“hot moments”). Hot spots were predominantly found in shallow areas (Ostrovsky 2003; Grinham et al. 2011; Zheng et al. 2011; Deshmukh et al. 2014; Natchimuthu et al. 2016;
de Mello et al. 2018), in areas close to tributary river inflows (DelSontro et al. 2011; Zhao et al. 2013; Musenze et al. 2014; Beaulieu et al. 2016; Descloux et al. 2017; Harrison et al. 2017; Tuşer et al. 2017; de Mello et al. 2018; Hilgert et al. 2019), and in areas with high sediment accumulation (Sobek et al. 2012; Maecck et al. 2013; Hilgert et al. 2019), high organic carbon content (Grinham et al. 2018; Hilgert et al. 2019), or high organic matter reactivity (Sobek et al. 2012). Hot moments of ebullition tend to correlate positively with air temperature (DelSontro et al. 2010; Maecck et al. 2013; Vik et al. 2013; Peixoto et al. 2015; Wilkinson et al. 2015; Natchimuthu et al. 2016), bottom water temperature (Deshmukh et al. 2014), sediment temperature (Tuşer et al. 2017), low hydrostatic pressure (Ostrovsky 2003; Varadharajan and Hemond 2012; Vik et al. 2013; Deshmukh et al. 2014; Harrison et al. 2017; Grinham et al. 2018), and low air pressure (Mattson and Likens 1990; Deshmukh et al. 2014; Grinham et al. 2018; Marcon et al. 2019). Interestingly, some authors have mentioned a shift in spatial variability of CH4 ebullition over time. For example, high-flux zones can shift seasonally from shallower to deeper regions in subarctic lakes (Vik et al. 2013) or temperate reservoirs (Tuşer et al. 2017), presumably as a result of seasonal changes in sediment temperature (Tuşer et al. 2017). Similarly, it has also been suggested that CH4 emission from shallower lakes responds stronger to temperature than that from deeper lakes (Natchimuthu et al. 2016).

While there are a number of studies that measured CH4 ebullition in reservoirs at low latitudes, both in the tropics (Keller and Stallard 1994; Abril et al. 2005; Ramos et al. 2006; DelSontro et al. 2011; de Mello et al. 2018) and subtropics (Grinham et al. 2011; Deshmukh et al. 2014; Beaulieu et al. 2016; Guérin et al. 2016; Grinham et al. 2018; Yang et al. 2018; Hilgert et al. 2019; Marcon et al. 2019), only a few of them (Keller and Stallard 1994; Deshmukh et al. 2014; Yang et al. 2018; Marcon et al. 2019) have studied temporal trends of ebullition in enough detail to identify seasonal trends. None of these studies have systematically compared the magnitude of the variability of CH4 ebullition over scales of both space and time. Furthermore, very few studies have measured ebullitive emission from reservoirs at a high spatial resolution using an echosounder (DelSontro et al. 2010; DelSontro et al. 2011; Maecck et al. 2013; Maecck and Lorke 2014; Tuşer et al. 2017), and only one of those studies was on a tropical reservoir (DelSontro et al. 2011). Hence, our understanding of CH4 ebullition in low-latitude reservoirs is limited by a lack of quantitative information on its spatiotemporal variability, despite indications that CH4 emissions from reservoirs of these regions are some of the highest worldwide (St. Louis et al. 2000; Barros et al. 2011; Deemer et al. 2016).

Here, we present results from a large bay with a river inflow in the oligotrophic water supply reservoir Chapéu d’Uvas (CDU) in the Atlantic Forest biome of Southeastern Brazil, situated at the threshold of the tropical and subtropical climate zone. We performed measurements of CH4 ebullition at high spatial resolution using a hydroacoustic echosounder and bubble traps at (1) an intra-annual scale, with one survey per month over 1 year and (2) an intra-monthly scale with one survey every 2–3 d over 3 weeks (2 weeks with hydroacoustics). We also include results from (3) a diel study with continuous measurements at 3-h time intervals over 24 h (A. Linkhorst et al., unpubl.). For further understanding of variability, we studied the drivers of CH4 ebullition at each timescale. Thus, we quantify the magnitude and variability of CH4 ebullition over different timescales (from diel to seasonal) at a high spatial resolution along with its main drivers in a low-latitude reservoir. The overall aim was to determine the best way to representatively measure CH4 ebullition with minimum sampling effort.

Methods

Sampling site and general setup

The studied bay of CDU reservoir in Brazil (see Table S1 for its characteristics) is roughly 2 km long, with an area of 0.326 km2 and a maximum depth of 15 m, and it is characterized by a river inflow in its northern end with a catchment area of 20 km2 covered by grassland and forest patches. We measured CH4 ebullition with high spatial resolution using bubble traps and a hydroacoustic echosounder at three temporal scales: once a month between August 2015 and August 2016 (intra-annual scale), every 2–3 d over a period of 22 d in November to December 2016 (intra-monthly scale), and continuously over 24 h with the data binned in 3-h intervals on 09–10 May 2016 (diel study; A. Linkhorst et al., unpubl.). We also measured CH4 concentrations in sediment pore water before and after the intra-monthly study on 18 November 2016 and 16 December 2016, and further analyzed sediment and preflooding soil properties from cores taken on 29 March 2018.

CH4 ebullition

We measured CH4 ebullition using bubble traps combined with a spatial hydroacoustic echosounder survey at each sampling occasion. For the intra-annual scale, we covered the whole bay, and for the intra-monthly scale, we covered only the northern part of the bay closest to the river inflow, which was expected to be a hot spot of CH4 ebullition (DelSontro et al. 2011; Maecck et al. 2013). The sampling scheme is illustrated in Fig. S1. For the intra-annual scale, we sampled on 18 August 2016, 19 September 2016, 24 October 2016, 09 March 2017, 31 March 2017, 21 April 2017, 25 May 2017, 03 July 2017, and 03 August 2017. For the intra-monthly scale, we sampled on 25 November 2016, 28 November 2016, 30 November 2016, 02 December 2016, 05 December 2016, 07 December 2016, 09 December 2016, 12 December 2016, 14 December 2016, and 16 December 2016. November is often the beginning of the rainy season, which was expected to result in changes of system properties and potentially ebullition fluxes.

For hydroacoustic measurements, we used a Simrad EY60 portable scientific echosounder (Kongsberg Maritime AC, Norway) with a 120-kHz split-beam transducer (downward facing,
Hydroacoustic data were analyzed with Sonar5 Pro (Lindem Acquisiton, Norway), which enables distinction between bubbles and fish/plankton based on their travel path, velocity and signal intensity (Ostrovsky et al. 2008; DelSontro et al. 2011). Each hydroacoustic file was divided into segments of 300 ± 5 pings, which equates to distances of ~24 m for the intra-annual scale and ~10 m for the intra-monthly scale. Bubble density was determined per water volume covered by the echosounder beam and converted into bubble gas flux following DelSontro et al. (2011, 2015) and accounting for bubble dissolution during rise using the model described in McGinnis et al. (2006), assuming an average CH4 content of 70% in the bubbles (discussed in Text S1). We used only the 3 m closest to the sediment for further data analysis and excluded any hydroacoustic measurement in the near-field zone of the transducer (~1.5 m). During the intra-monthly study, echosounder measurements were conducted only over 15 d of the 22-day study period (02–16 December 2016) due to an instrument failure.

For the ebullition measurements with the bubble traps, we used custom-built conical plastic frames (50 cm in diameter, 43 cm tall) covered with impermeable tarp and equipped with 220-mL glass bottles screwed into threads at the narrow ends of the funnels. For the intra-annual scale, we distributed four to seven bubble traps along the northern part of the bay. For the intra-monthly scale, we distributed 14 bubble traps along a longitudinal transect in the northern part of the bay, alternatingly close to the shore and in the middle (Fig. S1b,c). Each bubble trap was attached to a buoy in 1.5-m distance, which was anchored, so that it could move around the buoy in a radius of 1.5 m. The bubble traps were completely submerged in water, and the bottles were filled with water and screwed on top of the traps at the beginning of each trap deployment. Gas in the glass bottles was sampled after 3–5 h with a syringe, and CH4 concentrations were determined by injection into an ultraportable greenhouse gas analyzer (UGGA, Los Gatos Research) within the same day (see Paranaiba et al. 2018, for details on manual gas injection of discrete samples into the UGGA). We injected 3–7 mL as we found that at our concentrations, we need at least 3 mL of gas for robust CH4 concentration measurements. The volume of the captured gas was determined by measuring the water volume in the glass bottle after deployment and subtracting this volume from its maximum capacity of 220 ± 2 mL.

Hydroacoustic measurements can cover space but are limited in temporal coverage. Bubble traps are fixed in space and cover a very small area, but integrate over the duration of deployment. In shallow water depths (0–3 m), hydroacoustics cannot be used at all, whereas bubble traps as ours (50 cm height) can be deployed at depths of less than 1 m. Therefore, the results gained from these two methods cannot be directly compared to each other.

The data sets for the intra-annual scale and the intra-monthly scale are presented as independent data sets, as the methodological approach slightly differed; whereas we covered the whole bay with hydroacoustic surveys for the intra-annual scale, we covered only the northern part of the bay for the intra-monthly scale. Although at both intra-annual and intra-monthly study we had bubble traps distributed only in the northern part of the bay, they were differently distributed, and twice as abundant for the intra-monthly than for the intra-annual study.

Sediment properties and CH4 pore-water concentrations

Sediment cores for determination of sediment characteristics were taken using a UWITEC gravity corer equipped with a hammer device on 29 March 2018, directly at the spots where bubble traps had been deployed during the intra-monthly sampling (Fig. S1c). Each core was separated into post-flooding sediment and pre-flooding soil by visual distinction in color and texture, and each of the layers was homogenized separately. We analyzed each homogenized layer of each core for grain size distribution, total organic carbon (TOC) content and total nitrogen (TN) content (methods are described in Text S2), and calculated the molar carbon to nitrogen (C/N) ratio. Sediment cores for CH4 pore-water content were taken at spots as illustrated in Fig. S1c once before and once after the intra-monthly sampling, on 18 November 2016 and 16 December 2016. CH4 concentrations were analyzed for each 2-cm layer down each of the cores, as further described in Text S3.

Environmental variables

A 24-h average of air temperature and barometric pressure was taken from the nearest weather station in Juiz de Fora (INMET, Brazilian National Institute of Meteorology) for each sampling day. During each survey, we measured water temperature (YSI 6600 V2 for intra-annual scale; HOBO Water Temperature Pro v2 for intra-monthly scale) every 1 m depth in the water column at one location with a mean depth of ~12 m (10–17 m) for the intra-annual scale and ~8 m (7.7–8.7 m) for the intra-monthly scale (see Fig. S1b,c for the profile locations). Temperature depth profiles were assumed to apply to the entire bay area. The range in maximum depth at the locations for the water temperature profiles varied mostly with variations in water level, but also because of minor variations in location of the profile. Total pressure change at the sediment–water interface per sampling day was calculated from the difference in water level (measured daily and provided by the dam operator CESAMA) between the previous day and the actual sampling day, where we assumed a pressure of 100 mbar per 1 m water column height, plus the difference in atmospheric pressure (as averaged over 24 h) between the previous day and the actual sampling day.

Bathymetry was extracted from the data points of all hydroacoustic surveys, which yielded a total number of 3869 depth measurements, where each depth measure represents an area of about 7–17 m² (segments of 10 and 24 m for intra-annual...
and intra-monthly study, respectively, multiplied by a mean beam width of 0.7 m at a mean depth of 6 m). The total coverage for the bathymetry and hydroacoustic flux measurements is shown in Fig. S2.

Calculations and statistics
The CH$_4$ ebullition from each hydroacoustic survey was interpolated with Inverse Distance Weighting (ArcGIS version 10.6.1) across the whole bay for the intra-annual scale, and across the northern part of the bay for the intra-monthly scale. It was then gridded to cells of 0.0006° × 0.0006° (decimal degrees, dd; see Text S4 for optimal cell size determination), which is equivalent to 66.43 × 66.17 m at 21° latitude. For each sampling day, we extracted the mean CH$_4$ ebullition of each grid cell, which is the mean of all values produced by the interpolation within each grid cell.

For each grid cell, we then averaged the means from all sampling days, which we hereafter refer to as the “temporally resolved mean” for each grid cell. For our “spatiotemporally resolved” total CH$_4$ ebullition estimate for the whole bay, we then averaged all temporally resolved means from the intra-annual scale, and multiplied them by the total area of grid cells. In addition to these calculations, we interpolated the temporally resolved means of all grid cells, separately for the intra-annual and the intra-monthly scale, to create maps of temporally resolved CH$_4$ flux for each temporal scale study. For each grid cell, we also calculated the coefficient of variance (CV) between the means of the different sampling occasions as an expression of temporal variability, which was then interpolated for mapping purposes for the two temporal scale studies.

For comparing the variability of ebullition at different temporal and spatial scales, we used the frequency distribution of the quartile coefficient of dispersion (QCD), which is a measure of variability suitable for comparisons of data sets with non-normally distributed residuals (Bonett 2006),

$$\text{QCD} = \frac{Q_3 - Q_1}{Q_3 + Q_1},$$  

where Q1 and Q3 are the first and third quartile of a data set, respectively. The QCD can have values between 0 and 1, where a high value indicates high variability. The methods behind these frequency distribution plots for spatiotemporal comparisons are explained in further detail in Text S5 and Fig. S3.

Calculations were done in R version 3.5.2 and Matlab version R2018a, spatial analyses in ArcGIS version 10.6.1 and all other graphics in R.

Results
Spatial variability of CH$_4$ ebullition
We found that high CH$_4$ ebullition (up to 1572 mg C m$^{-2}$ d$^{-1}$ annual mean in one grid cell) can occur at multiple depths and locations along the bay, from the shallow northern part of the bay close to the river inflow (0–5 m) to the deeper part further south (10–15 m; Fig. 1a). In the intra-annual data, which cover the entire bay, we observed areas of high annual mean CH$_4$ ebullition closest to the river inflow, but also in the middle and in the southern end of the bay (Fig. 1b). The intra-monthly data, which cover the northern part of the bay only, also reveal highest mean CH$_4$ ebullition closest to the river inflow as well as patches of high ebullition further downstream (Fig. 1d). The mean spatiotemporally resolved CH$_4$ ebullition at the intra-monthly scale (Fig. 1d, 270 mg C m$^{-2}$ d$^{-1}$) was similar to the mean temporally and spatially resolved CH$_4$ ebullition at the intra-annual scale (Fig. 1b, 281 mg C m$^{-2}$ d$^{-1}$), but the spatial variability of mean CH$_4$ ebullition between grid cells was much larger at the intra-annual scale (Fig. 1b, range: 38–1572 mg C m$^{-2}$ d$^{-1}$) compared to at the intra-monthly scale (Fig. 1d, range: 64–704 mg C m$^{-2}$ d$^{-1}$).

There was no apparent relationship between water depth and CH$_4$ ebullition. Binning all hydroacoustic CH$_4$ ebullition flux data (intra-annual + intra-monthly scale) into categories of 1.5–3, 3–5, 5–10, and 10–15 m (Fig. 2a) and all bubble trap data into categories of 0.9–3, 3–5, and 5–8 m (Fig. 2b) revealed a similar magnitude and variability of CH$_4$ ebullition flux for all depth categories. Mean fluxes in the shallowest depth categories from the hydroacoustic and bubble trap data sets were similar (1.5–3 m: 256 mg C m$^{-2}$ d$^{-1}$ vs. 0.9–3 m: 230 mg C m$^{-2}$ d$^{-1}$). Interestingly though, highest fluxes observed in the bubble trap data were in this shallow zone, whereas CH$_4$ ebullition was highest in the deepest bins of the hydroacoustic data set (10–15 m, 569 mg C m$^{-2}$ d$^{-1}$). Ultimately, CH$_4$ ebullition estimated via the hydroacoustic approach varied over four to five orders of magnitude within each depth category, presumably due to the much higher spatial resolution achieved at all depths with the echosounder surveys (Fig. 2a) compared to that achieved with bubble trap deployments (Fig. 2b).

Temporal variability of CH$_4$ ebullition
The variability of CH$_4$ ebullition over time was calculated for each grid cell as the CV, which was highest in the northern part of the bay (Fig. 1c) in close proximity to the river inflow (Fig. 1e), indicating more temporal variability in the northern part compared to the southern part of the bay. At an intra-annual timescale, both bubble trap data and hydroacoustic data showed that CH$_4$ ebullition was highest on 9 March during falling water level, and lowest on 03 July during rising water level (Figs. 3a, S4, S5a; Table S4). However, the range in mean fluxes across the year (i.e., mean flux from all grid cells for each sampling day) using the hydroacoustic approach was 581–1271 mg C m$^{-2}$ d$^{-1}$, which is roughly twice as high as those from the bubble traps (44–527 mg C m$^{-2}$ d$^{-1}$), likely illustrating the difference in spatial coverage resolution between the two approaches (discussed below). At an intra-monthly timescale, bubble trap data showed highest mean flux occurring on 07 December and the lowest flux 2 days later on 09 December (Fig. 3b, Table S4), which was the date that the hydroacoustic data recorded its highest flux of the intra-monthly survey (lowest was 16 December; Fig. S5b). Again,
Hydroacoustic data were the most variable during the month with mean fluxes of 5–470 mg C m$^{-2}$ d$^{-1}$ compared to 5–293 mg C m$^{-2}$ d$^{-1}$ for the bubble trap data (Table S4). Ultimately, a higher degree of CH$_4$ ebullition variability was found over the entire year (hydroacoustics: 581–1271 mg C m$^{-2}$ d$^{-1}$, bubble traps: 44–527 mg C m$^{-2}$ d$^{-1}$; Table S3) than over a single month that was characterized by intermediate fluxes (hydroacoustics: 5–470 mg C m$^{-2}$ d$^{-1}$, bubble traps: 5–293 mg C m$^{-2}$ d$^{-1}$; Table S4).

**Comparison of spatial and temporal variability of CH$_4$ ebullition**

As the greatest spatial and temporal coverage was acquired by the hydroacoustic surveys, we primarily use this data set to investigate both the spatial and temporal variability of CH$_4$ ebullition. At the intra-annual timescale, the spatial variability of CH$_4$ ebullition was comparable to the temporal variability on about half of the sampling occasions, visible via the overlap in QCD distributions in Fig. 4a. On the other half of the sampling occasions, however, CH$_4$ ebullition was less variable in space than in time as indicated by the smaller QCD values for the intra-annual spatial data set. CH$_4$ ebullition varied strongly in both space and time in the intra-monthly data, but the temporal variability was greater than the spatial variability (i.e., higher QCD range for intra-monthly temporal variability in Fig. 4a).

Comparing the QCD distributions of both temporal scales (Fig. 4a), we find that CH$_4$ ebullition varied more at the intra-
annual timescale than at the intra-monthly timescale. Similarly, the spatial variability of CH$_4$ ebullition was more pronounced throughout the intra-annual study than during the intra-monthly study (i.e., intra-annual QCD distribution range was higher in Fig. 4a). We also investigated the temporal variability in CH$_4$ ebullition at fixed locations over multiple timescales using bubble trap data (Fig. 4b). For this comparison, we added measurements of CH$_4$ ebullition over one diel cycle at one location at the northernmost area of the same bay (A. Linkhorst et al., unpubl.) to the bubble trap measurements we present here. Ultimately, the temporal variability in CH$_4$ ebullition was similarly high at diel, intra-monthly and intra-annual timescales, but a larger range in variability was observed at the longer timescales (Fig. 4b).

**Characteristics and CH$_4$ pore-water content of sediment and pre-flooding soil**

The thickness of postflooding sediment varied between 0 and 32 cm. TOC and TN content, as well as the C/N ratio, were higher in the post-flooding sediment than in the pre-flooding soil (Table S5). There was no systematic difference in the median particle size between sediment and pre-flooding soil (Table S5). Multivariate analyses (principal components analysis and partial least squares regression; not shown) showed no significant relationships between CH$_4$ ebullition and sediment thickness or characteristics of adjacent cores. Mean CH$_4$ porewater concentration at the five cores sampled for CH$_4$ porewater profiles was 323–1245 μM on 18 November 2016 and 1426–4024 μM on 16 December 2016 (Table S2; Fig. S6).
Environmental variables

The water level fluctuated 4.9 m over the intra-annual study with four samplings during falling water and five samplings during rising water (Fig. S4). During the intra-monthly study, water level fluctuated only by 0.2 m without a clear overall rising or falling trend. Daily mean air temperature (24 h average) was on average 18.2°C (range: 13.4–21.6°C) during the intra-annual study and 19.9°C (range: 15.2–22.6°C) during the intra-monthly study. Mean surface water temperature during sampling was 24.1°C (range: 19.6–29.0°C) and 27.3°C (range: 25.4–29.5°C), and mean bottom water temperature during sampling was 23.4°C (range: 19.7–28.3°C) and 25.1°C (range: 24.4–25.9°C) for the intra-annual and intra-monthly studies, respectively (see Tables S3, S4 for more details).

Discussion

Variability of CH₄ ebullition at temporal and spatial scales

While many previous studies have pointed out the importance of spatial variability in low-latitude reservoir CH₄ ebullition (Grinham et al. 2011; DelSontro et al. 2015; Hilgert et al. 2019), and some others have found seasonal patterns (Deshmukh et al. 2014; Yang et al. 2018; Marcon et al. 2019), this is, to our knowledge, the first study to systematically compare the variability of CH₄ ebullition both spatially and over different scales of time.

We found that CH₄ ebullition varied strongly in both space and time, but that the temporal variability of CH₄ ebullition was in general more pronounced than its spatial variability, at both the intra-annual and at the intra-monthly scale (Fig. 4a). We conclude that measurements of CH₄ ebullition made seasonally are likely to capture the most pronounced variability in emission from our study system. The variability of CH₄ ebullition as measured from the bubble traps over 24 h at one site was similar in magnitude as the variability at intra-monthly (at 14 sites) and intra-annual timescales (at 4–7 sites). However, the total range in variability was smaller for our diel study than for at the intra-monthly and intra-annual timescales. In two studies with measuring automated bubble traps over 5 months in a temperate reservoir (Maeck et al. 2014) and over 1 year in a subtropical reservoir in Brazil (Marcon et al. 2019), ebullition rates also varied strongly over different timescales from minutes to days. Differences between seasons were suggested to be due to seasonal temperature differences (Maeck et al. 2013, 2014) or stratification and mixing dynamics (Marcon et al. 2019). With respect to variability on shorter time scales, no diel variability was observed during monitoring of CH₄ ebullition in the subtropical Brazilian reservoir (Marcon et al. 2019). Eddy covariance studies (Eugster et al. 2011; Deshmukh et al. 2014; Podgrajsek et al. 2016) achieve high temporal resolution over different scales but since they cannot distinguish between diffusive and ebullitive emission, their findings of temporal variability at different scales are not directly comparable to our results.

Our analysis also shows that the spatial variability in CH₄ ebullition can be high (Fig. 4a), even in relatively small areas such as our study bay (0.326 km²). It is possible that increasing the survey area will result in greater overall spatial variability of ebullitive emission, because other areas will have different depth, and possibly different sediment characteristics and deposition rate, as well as bottom water properties. To attain representative measurements of system-wide CH₄ ebullition, it is crucial that measurements are distributed in space as well as in time.
Drivers of temporal variability

The temporal variability of CH4 ebullition measured via both the hydroacoustic and bubble trap approaches was related to water level, pressure changes on the sediment, as well as surface and bottom water temperature (Fig. 5; Tables S3, S4). The highest fluxes occurred at low water level (see Fig. S4 for a hydrograph) for both timescales of the hydroacoustic data (Fig. 5a,e), but patterns were less evident for bubble trap data, which admittedly cover a much smaller surface area. Low water level translates into lower hydrostatic pressure on the sediment, which eases the release of bubbles from the sediment, a phenomenon that has been observed in temperate reservoirs (Maeck et al. 2014; Harrison et al. 2017). Accordingly, CH4 ebullition was higher during periods of decreasing pressure on the sediment than during periods of increasing pressure on the sediment (Fig. 5b,f), in agreement with previous studies (Mattson and Likens 1990; Ostrovsky 2003; Harrison et al. 2017). However, temperature variability between dry rainy season may also likely have played a role, and without experimental work, it is difficult to disaggregate the physical from the biological drivers.

Temperature has a strong positive effect on CH4 production rates (Yvon-Durocher et al. 2014) and CH4 ebullition (Aben et al. 2017). Both bottom and surface water temperature were related to mean ebullitive CH4 flux across the study areas (Fig. 5c,d,g,h). Surface water temperature was a good predictor of CH4 ebullition for both timescales, albeit less so at the intra-monthly timescale when temperature varied less (Fig. 5c,g). Bottom water temperature from the temperature profile locations was positively related to CH4 ebullition measured via both approaches at the intra-annual timescale (Fig. 5d).

Drivers of spatial variability

Some previous studies have found significant relationships between CH4 ebullition and depth in reservoirs (Keller and Stallard 1994; Deshmukh et al. 2014), whereas others have not (DelSontro et al. 2011, 2015; Hilgert et al. 2019). We did not find a consistent trend of CH4 ebullition variability over water depth in our study area (Fig. 5), and even though the bathymetric information is based on high-resolution measurements (Fig. S2), we cannot exclude that averaging both water depth and ebullition flux per grid cell may hide smaller-scale patterns. Furthermore, spatial variability in CH4 ebullition appears not to be related to distance from the shore as high fluxes were found throughout the bay (Fig. 1b), contrary to what has been reported for a tropical floodplain lake (Peixoto et al. 2015). High ebullitive fluxes were observed in the shallow area (1–5 m) closest to the river inflow but also in the...
at least one depth layer where CH$_4$ was oversaturated (Fig. S6), CH$_4$ layers in pre-flooding soils (Fig. S6; Table S2). However, the sampled spots were shallow enough (<9 m) to be exposed to air at least for 1-month long periods during previous extreme dry seasons (see historical water level in Fig. S7). Therefore, even though we observed ebullition coming from deep layers that we determined as pre-flooded soils, it might be that those layers were fed by fresh terrestrial organic material when roots of terrestrial plants have entered deeper bottom layers during exposure to the atmosphere. As fresh land plant material can rapidly be degraded to CH$_4$ at anoxic conditions (Grasset et al. 2018), this fresh input of organic matter likely stimulated high CH$_4$ production rates upon inundation prior to our study (Prairie et al. 2018). The water level fluctuated over a total range of 15 m between 2003 and 2016, with a water level fluctuation between dry and rainy season of 6–13 m (Fig. S7). Essentially, this means that large areas of the reservoir bottom have at some point been exposed to the atmosphere and may contain rather fresh organic material in their deep bottom layers. Because of the supply of fresh organic material, these parts of the reservoir bottom can emit CH$_4$ even 22 years after dam construction and initial flooding of the land.

Comparison of different upscaling scenarios

We upscaled CH$_4$ ebullition for the entire study area using different temporal and spatial resolutions to investigate the effect of measurement variability on upscaled estimates. The upsampling scenarios as shown in Fig. S8 and Table 1 are compared to our spatiotemporally resolved best estimate (33 t C yr$^{-1}$; Fig. 1b), which is based on the interpolation of spatially resolved hydroacoustic CH$_4$ ebullition measurements at a monthly resolution over 1 year. The first scenario extrapolates from a single, yet spatially resolved, measurement occasion to an annual flux, similar to DelSontro et al. (2011). Extrapolation from the lowest and highest mean fluxes that we observed during our annual survey (09 March and 03 July) to the whole year led to CH$_4$ emission of 8 and 81 t C yr$^{-1}$ from our study area, respectively. Extrapolation from the months of lowest and highest flux during the year thus differed by 76% and 145% from our best estimate (Fig. S8b,c; Table 1), illustrating the significance of seasonally resolved measurements of CH$_4$ ebullition for calculating whole-system estimates.

The second scenario extrapolates total flux from measurements at only a few locations but over several sampling occasions, similar to Dos Santos et al. (2006). Performing extrapolations using only data from areas with the highest ebullitive fluxes (as derived from interpolation of our measured fluxes, spots marked in Fig. S8d) would overestimate total CH$_4$ ebullition by 174% (92 t C yr$^{-1}$) compared to our spatiotemporally resolved best estimate (33 t C yr$^{-1}$). If, on the other hand, we extrapolated using only data from the areas with lowest ebullition (spots marked in Fig. S8e), we would underestimate the total flux by 79% (7 t C yr$^{-1}$; Table 1). Although these are worst-case scenarios, we can conclude that disregarding spatial variability also risks introducing large errors in whole-system estimates of CH$_4$ ebullition. Ultimately, spatially resolved measurements at seasonal temporal resolution are required for robust quantification of CH$_4$ ebullition.

The third scenario extrapolates total flux from measurements of the bubble traps, which compared to hydroacoustic surveys have low spatial resolution but integrate over longer temporal scales at fixed sites. Upscaling from the temporally resolved bubble trap measurements of the inter-annual study (4–7 traps in the northern part of the bay; Fig. S8f) to the

CH$_4$ pore-water concentration in sediment and pre-flooding soil

We measured CH$_4$ concentrations in the pore water of sediment and pre-flooding soil before and after the intra-monthly study to see if we can explain total CH$_4$ ebullition by an equivalent loss in CH$_4$ from the sediment. However, CH$_4$ concentrations in the pore water were higher at the end of the intra-monthly sampling campaign than at its start, indicating that CH$_4$ concentrations fluctuate over shorter timescales than 1 month. Nevertheless, 7 of 10 pore-water profiles contained at least one depth layer where CH$_4$ was oversaturated (Fig. S6), indicating that the sediment is prone to form and release bubbles, in congruence with the measured ebullitive CH$_4$ fluxes.

Interestingly, in 5 of 10 profiles, we observed supersaturated CH$_4$ layers in pre-flooding soils (Fig. S6; Table S2). However, the sampled spots were shallow enough (<9 m) to be exposed to air at least for 1-month long periods during previous extreme dry seasons (see historical water level in Fig. S7). Therefore, even though we observed ebullition coming from deep layers that we determined as pre-flooded soils, it might be that those layers were fed by fresh terrestrial organic material when roots of terrestrial plants have entered deeper bottom layers during exposure to the atmosphere. As fresh land plant material can rapidly be degraded to CH$_4$ at anoxic conditions (Grasset et al. 2018),

this high-flux area closest to the river inflow was characterized by high temporal variability in ebullition, while the high-flux area in the southern end of the bay did not vary as much over the year (Fig. 1c). The lack of direct relationship between CH$_4$ ebullition and water depth may be related to the heterogeneity of sediment deposition and bottom morphometry of reservoirs (Mendonça et al. 2014), particularly near a river inflow; however, in contrast to other studies (Sobek et al. 2012; Wilkinson et al. 2015; Grinham et al. 2018; Hilgert et al. 2019), our own data do not indicate any relationship between sediment characteristics (i.e., OC content, N content, C/N ratio, grain size, thickness of the sediment layer; Table S5) and CH$_4$ ebullition (not shown). This may be due to the lower water level in the dry seasons such as during the extreme drought in 2014 (Kosten et al. 2018), during which we observed that the shallowest areas closest to the river inflow (0–5 m) had dried out and were covered with grass. This fresh input of organic matter likely stimulated high CH$_4$ production rates upon inundation prior to our study (Prairie et al. 2018), and may blur relationships with sediment characteristics. Also, we lack core sampling sites in the southernmost part of the bay, an area with high CH$_4$ ebullition. We included information on sediment accumulation from three additional sediment cores from the southern part of the bay (Table S6), which, however, did not show higher sediment deposition rates than in the shallower northern part of the bay.
Table 1. Mean, median and total ebullitive CH₄ emission for different upscaling scenarios. The total flux was calculated from the product of the mean flux and total bay area (0.326 km²). The star marks our best estimate, based on spatiotemporally resolved hydroacoustic measurements, using the mean from all grid cells from all sampling campaigns over the year (Fig. 1b). The other upscaling scenarios are illustrated in Fig. S7.

| Scenario | Time | Data set | Mean flux (mg C m⁻² d⁻¹) | Median flux (mg C m⁻² d⁻¹) | Total flux (t C yr⁻¹) |
|----------|------|----------|--------------------------|---------------------------|----------------------|
| 1        | Whole year | Hydroacoustics, intra-annual | 281 | 195 | 33 |
| 09 Mar. 2017 (survey with highest flux) | Hydroacoustics, intra-annual | 681 | 385 | 81 |
| 03 Jul. 2017 (survey with lowest flux) | Hydroacoustics, intra-annual | 71 | 4 | 8 |
| 2        | Whole year | Hydroacoustics, intra-annual, 20 grid cells of highest flux | 769 | 640 | 92 |
| Whole year | Hydroacoustics, intra-annual, 20 grid cells of lowest flux | 62 | 62 | 7 |
| 3        | Whole year | Bubble traps, intra-annual, upscaled according to bathymetry | 173 | 128 | 21 |

entire bay area by means of bathymetry (i.e., applying the CH₄ ebullition means of the depth categories in Fig. 2) results in a total ebullitive CH₄ flux of 21 t C yr⁻¹, underestimating our spatiotemporally resolved best estimate by 36%.

This result illustrates the potential effect of low spatial resolution when sampling, but also the fact that bubble traps were only deployed at depths of 0.9–8 m in the northern part of the bay, thereby missing high ebullition areas in the south of the bay that were only recorded by the hydroacoustic surveys. This difference in spatial resolution and total areal coverage most likely led to the large discrepancy in daily mean CH₄ ebullition between hydroacoustic surveys (581–1271 mg C m⁻² d⁻¹; Fig. S5a) and bubble trap deployments (44–527 mg C m⁻² d⁻¹; Fig. 3a). The overall lower mean fluxes measured by bubble trap deployments compared to hydroacoustics indicate that a better temporal resolution of CH₄ ebullition does not necessarily compensate for lower spatial resolution.

Implications

Our study shows that to derive a robust estimate of CH₄ ebullition from a tropical reservoir, measurements must be conducted during different seasons of the year, at least once during falling and once during rising water level, and that these measurements should be spatially well resolved as well. Hydroacoustics is currently the most well-suited method for accomplishing seasonally distributed samplings at high spatial coverage. Time is the biggest constraint for using an echo-sounder to sufficiently resolve ebullition variability over time and space. For example, each individual hydroacoustic survey of our studied bay took about 2.3 h, but we only covered 3% (i.e., 0.326 km²) of this relatively small reservoir (12 km²).

While our study indicates that a few seasonally distributed measurement campaigns are required to capture the most pronounced temporal variability in CH₄ ebullition, a challenge for future studies is how to select sampling locations within individual systems for representative measurements of the variability of system-wide CH₄ ebullition, especially in large waterbodies in which even massive sampling efforts will only be able to cover a minute fraction of the total area. Unfortunately, we cannot offer a concrete advice regarding the spatial resolution necessary for accurate system-wide estimates of CH₄ ebullition, but we do suggest measuring flux in river inflow bays as well as regions not influenced by such external inputs. It cannot be overstated either that the hydroacoustic approach better resolved the spatial variability in ebullitive flux in all regions than a dozen randomly placed bubble traps did.

References

Aben, R. C. H., et al. 2017. Cross continental increase in methane ebullition under climate change. Nat. Commun. 8: 1–8. doi:10.1038/s41467-017-01535-y
Abril, G., and others. 2005. Carbon dioxide and methane emissions and the carbon budget of a 10-year old tropical reservoir (Petit Saut, French Guiana). Global Biogeochem. Cycles 19: 1–16. doi:10.1029/2005GB002457
Barros, N., J. J. Cole, L. Tranvik, Y. T. Prairie, D. Bastviken, V. L. M. Huszar, P. del Giorgio, and F. Roland. 2011. Carbon emission from hydroelectric reservoirs linked to reservoir age and latitude. Nat. Geosci. 4: 593–596. doi:10.1038/ngeo1211
Beaulieu, J. J., M. G. McManus, and C. T. Nietch. 2016. Estimates of reservoir methane emissions based on a spatially balanced probabilistic-survey. Limnol. Oceanogr. 61: 827–840. doi:10.1002/lno.10284
Bonett, D. G. 2006. Confidence interval for a coefficient of quartile variation. Comput. Stat. Data Anal. 50: 2953–2957. doi:10.1016/j.csda.2005.05.007
Cole, J. J., and others. 2007. Plumbing the global carbon cycle: Integrating inland waters into the terrestrial carbon budget. Ecosystems 10: 171–184. doi:10.1007/s10021-006-9013-8
Deemer, B. R., and others. 2016. Greenhouse gas emissions from reservoir water surfaces: A new global synthesis. BioScience 66: 949–964. doi:10.1093/biosci/biw117
DelSontro, T., J. J. Beaulieu, and J. A. Downing. 2018. Greenhouse gas emissions from lakes and impoundments: Upscaling in the face of global change. Limnol. Oceanogr. Lett. 3: 64–75. doi:10.1002/lol2.10073

DelSontro, T., D. F. McGinnis, S. Sobek, I. Ostrovsky, and B. Wehrli. 2010. Extreme methane emissions from a Swiss hydropower reservoir: Contribution from bubbling sediments. Environ. Sci. Technol. 44: 2419–2425. doi:10.1021/es9031369

DelSontro, T., M. J. Kunz, T. Kempter, A. Wüst, B. Wehrli, and D. B. Senn. 2011. Spatial heterogeneity of methane ebullition in a large tropical reservoir. Environ. Sci. Technol. 45: 9866–9873. doi:10.1021/es2005545

DelSontro, T., D. F. McGinnis, B. Wehrli, and I. Ostrovsky. 2015. Size does matter: Importance of large bubbles and small-scale hot spots for methane transport. Environ. Sci. Technol. 49: 1268–1276. doi:10.1021/acs.est.4b06528

de Mello, N. A. S. T., L. S. Brighenti, F. A. R. Barbosa, P. A. Staehr, and J. F. Bezzera Neto. 2018. Spatial variability of methane (CH4) ebullition in a tropical hypereutrophic reservoir: Silted areas as a bubble hot spot. Lake Reserv. Manag. 34: 105–114. doi:10.1080/10402381.2017.1390018

Descloix, S., V. Chanudet, D. Serça, and F. Guérin. 2017. Methane and nitrous oxide annual emissions from an old eutrophic temperate reservoir. Sci. Total Environ. 598: 959–972. doi:10.1016/j.scitotenv.2017.04.066

Deshmukh, C., and others. 2014. Physical controls on CH4 emissions from a newly flooded subtropical freshwater hydropower reservoir: Nam Theun 2. Biogeosciences 11: 4251–4269. doi:10.5194/bg-11-4251-2014

dos Santos, M. A., L. P. Rosa, B. Sikar, E. Sikar, and E. O. dos Santos. 2006. Gross greenhouse gas fluxes from hydropower reservoir compared to thermo-power plants. Energy Policy 34: 481–488. doi:10.1016/j.enpol.2004.06.015

Drake, T. W., P. A. Raymond, and R. G. M. Spencer. 2018. Terrestrial carbon inputs to inland waters: A current synthesis of estimates and uncertainty. Limnol. Oceanogr. Lett. 3: 132–142. doi:10.1002/lo2.10055

Eugster, W., T. DelSontro, and S. Sobek. 2011. Eddy covariance flux measurements confirm extreme CH4 emissions from a Swiss hydropower reservoir and resolve their short-term variability. Biogeosciences 8: 2815–2831. doi:10.5194/bg-8-2815-2011

Grasset, C., R. Mendonça, G. Villamor Saucedo, D. Bastviken, F. Roland, and S. Sobek. 2018. Large but variable methane production in anoxic freshwater sediment upon addition of allochthonous and autochthonous organic matter. Limnol. Oceanogr. 63: 1488–1501. doi:10.1002/loa.10786

Grinham, A., S. Albert, N. Deering, M. Dunbabin, D. Bastviken, B. Sherman, C. E. Lovelock, and C. D. Evans. 2018. The importance of small artificial water bodies as sources of methane emissions in Queensland, Australia. Hydrol. Earth Syst. Sci. 22: 5281–5298. doi:10.5194/hess-22-5281-2018

Grinham, A., M. Dunbabin, D. Gale, and J. Udy. 2011. Quantification of ebullitive and diffusive methane release to atmosphere from a water storage. Atmos. Environ. 45: 7166–7173. doi:10.1016/j.atmosenv.2011.09.011

Guerin, F., and others. 2016. Effect of sporadic destratification, seasonal overturn, and artificial mixing on CH4 emissions from a subtropical hydroelectric reservoir. Biogeosciences 13: 3647–3663. doi:10.5194/bg-13-3647-2016

Harrison, J. A., B. R. Deemer, M. K. Birchfield, and M. T. O’Malley. 2017. Reservoir water-level drawdowns accelerate and amplify methane emission. Environ. Sci. Technol. 51: 1267–1277. doi:10.1021/acs.est.6b03185

Hilgert, S., C. V. Scapulatempo Fernandes, and S. Fuchs. 2019. Redistribution of methane emission hot spots under drawdown conditions. Sci. Total Environ. 646: 958–971. doi:10.1016/j.scitotenv.2018.07.338

Intergovernmental Panel on Climate Change (IPCC). 2013. In T. F. Stocker and others. [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, UK: Cambridge University Press, 1535 pp.

Keller, M., and R. F. Stallard. 1994. Methane emission by bubbling from Gatun Lake, Panama. J. Geophys. Res. 99: 8307–8319. doi:10.1029/92JD02170

Kosten, S., S. van den Berg, R. Mendonça, J. R. Paraiba, F. Roland, S. Sobek, J. Van Den Hoek, and N. Barros. 2018. Extreme drought boosts CO2 and CH4 emissions from reservoir drawdown areas. Inland Waters 8: 329–340. doi:10.1080/20442041.2018.1483126

Maack, A., T. DelSontro, D. F. McGinnis, H. Fischer, S. Flury, M. Schmidt, P. Fietzek, and A. Lorke. 2013. Sediment trapping by dams creates methane emission hot spots. Environ. Sci. Technol. 47: 8130–8137. doi:10.1021/es403907

Maack, A., H. Hofmann, and A. Lorke. 2014. Pumping methane out of aquatic sediments—Ebullition forcing mechanisms in an impounded river. Biogeosciences 11: 2925–2938. doi:10.5194/bg-11-2925-2014

Maack, A., and A. Lorke. 2014. Ship-lock-induced surges in an impounded river and their impact on subdaily flow velocity variation. River Res. Appl. 30: 494–507. doi:10.1002/rra.2648

Marcon, L., T. Bleninger, M. Männich, and S. Hilgert. 2019. High-frequency measurements of gas ebullition in a Brazilian subtropical reservoir—Identification of relevant triggers and seasonal patterns. Environ. Monit. Assess. 191: 357. doi:10.1007/s10661-019-7498-9

Mattsson, M. D., and G. E. Likens. 1990. Air pressure and methane fluxes. Nature 347: 718–719. doi:10.1038/347718b0

McGinnis, D. F., J. Greinert, Y. Artemov, S. E. Beaubien, and A. Wüst. 2006. Fate of rising methane bubbles in stratified waters: How much methane reaches the atmosphere? J. Geophys. Res. 111: C09007. doi:10.1029/2005JC003183

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
Tranvik, L., A. Grinham, U. Werner, D. Gale, K. Sturm, J. Udy, and Z. Yuan. 2014. Assessing the spatial and temporal variability of diffusive methane and nitrous oxide emissions from subtropical freshwater reservoirs. Environ. Sci. Technol. 48: 14499–14507. doi: 10.1021/es50324h
Natchimuthu, S., I. Sundgren, M. Gålfalk, L. Klemetsson, P. Crill, Å. Danielsson, and D. Bastviken. 2016. Spatio-temporal variability of lake CH$_4$ fluxes and its influence on annual whole lake emission estimates. Limnl. Oceanogr. 61: S13–S26. doi: 10.1002/lno.10222

Ostrovsky, I. 2003. Methane bubbles in Lake Kinneret: Quantification and temporal and spatial heterogeneity. Limnl. Oceanogr. 48: 1030–1036. doi: 10.4319/lo.2003.48.3.1030

Ostrovsky, I., D. F. McGinnis, L. Lapidus, and W. Eckert. 2008. Quantifying gas ebullition with echosounder: The role of methane transport by bubbles in a medium-sized lake. Limnl. Oceanogr. Methods 6: 105–118. doi: 10.4319/lom.2008.6.105

Paraíba, J. R., N. Barros, R. Mendonça, A. Linkhorst, A. Isidorova, F. Roland, R. M. Almeida, and S. Sobek. 2018. Spatially resolved measurements of CO$_2$ and CH$_4$ concentration and gas-exchange velocity highly influence carbon-emission estimates of reservoirs. Environ. Sci. Technol. 52: 607–615. doi: 10.1021/acs.est.7b05138

Peixoto, R. B., F. Machado-Silva, H. Marotta, A. Enrich-Prast, and D. Bastviken. 2015. Spatial versus day-to-day within-lake variability in tropical floodplain lake CH$_4$ emissions—Developing optimized approaches to representative flux measurements. PLoS One 10: e0123319. doi: 10.1371/journal.pone.0123319

Podgrajsek, E., E. Sahlée, D. Bastviken, S. Natchimuthu, N. Kljunc, H. E. Chmiel, L. Klemetsson, and A. Rutgersson. 2016. Methane fluxes from a small boreal lake measured with the eddy covariance method. Limnl. Oceanogr. 61: S41–S50. doi: 10.1002/lno.10245

Prairie, Y. T., and others. 2009. Lakes and reservoirs as regulators of carbon cycling and climate. Limnl. Oceanogr. 54: 2298–2314. doi: 10.4319/lo.2009.54.6_part_2.2298

Varadharajan, C., and H. F. Hemond. 2012. Time-series analysis of high-resolution ebullition fluxes from a stratified, freshwater lake. J. Geophys. Res. Biogeosciences Discuss.: 1–37. doi: 10.5194/bg-2018-195

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

Zhao, Y., B. F. Wu, and Y. Zeng. 2013. Spatial and temporal patterns of greenhouse gas emissions from three gorges reservoir of China. Biogeosciences 10: 1219–1230. doi: 10.5194/bg-2014-36

Zheng, H., X. Zhao, T. Zhao, F. Chen, W. Xu, X. Duan, X. Wang, and Z. Ouyang. 2011. Spatial-temporal variations of methane emissions from the Ertan hydroelectric reservoir in Southwest China. Hydrol. Process. 25: 1391–1396. doi: 10.1002/hyp.7903

**Acknowledgments**

We are grateful to Carlos Henrique Estrada for his help with the daily and monthly surveys, and Icaro Barbosa and Carlos Henrique Estrada for sediment sampling. The research leading to these results has been funded by the European Research Council under the European Union’s Seventh Framework Programme (FP7/2007-2013)/ERC grant agreement n° 336642. S.S. received additional support by the program Pesquisador Visitante Especial, Ciência sem Fronteiras, No. 401384/2014-4, and N. B. received additional support by Fundação de Amparo à Pesquisa do Estado de Minas Gerais/FAPEMIG (CRA APQ 03045/16).

**Conflict of Interest**

None declared.