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EDITED AND REVIEWED BY
Alexandre J. Poulain,
University of Ottawa, Canada

*CORRESPONDENCE
Daniel F. McGinnis,
daniel.mcginnis@unige.ch

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Editorial: Sources, sinks, and emissions in aquatic systems: the past, present, and future under global change

Daniel F. McGinnis[1]*, Yves T. Prairie[2], Hans-Peter Grossart[3,4] and Tonya DelSontro[5]

[1]Aquatic Physics Group, Department F.-A. Forel for Environmental and Aquatic Sciences (DEFSE), Faculty of Science, University of Geneva, Geneva, Switzerland, [2]UNESCO Chair in Global Environmental Change, Université du Québec à Montréal, Montréal, QC, Canada, [3]Department of Experimental Limnology, Leibniz Institute of Freshwater Ecology and Inland Fisheries, Stechlin, Germany, [4]Institute of Biochemistry and Biology, Potsdam University, Potsdam, Germany, [5]Department of Earth and Environmental Sciences, University of Waterloo, Waterloo, ON, Canada

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Editorial on the Research Topic
Sources, sinks, and emissions in aquatic systems: the past, present, and future under global change

Methane, a greenhouse gas with a high warming potential, is increasing at an alarming rate (Nisbet et al., 2019). While studies have quantified methane emissions through *in situ* measurements, fewer studies have sought a mechanistic understanding of methane dynamics in aquatic systems (Langenegger et al., 2019). The atmospheric methane contribution from inland and coastal waters remains largely uncertain due to the current mechanistic knowledge gaps and stochastic processes (Bastviken et al., 2011). Methane is unusual in aquatic systems because its oxidation can be nearly as large as its production, highlighting the importance of focusing on both sources and sinks (Thottathil et al., 2019).

The studies in this Research Topic include physical–biogeochemical processes driving methane cycling in both natural and artificial waterbodies, including drivers such as climate warming, eutrophication, and urbanization. Interdisciplinary studies present the effects and feedbacks between methane cycling on the waterbody ecology, physical–biogeochemical cycles, ecology, microbiology, and modeling. Study areas include all types of inland and ocean waters and local, regional, and global upscaling, as well as forecasting. The article types include original research, brief research reports, and reviews.

McClure et al. discussed the potential of near-term ecological forecasting to improve the predicting of sediment methane ebullition rates. The authors developed and tested a near-term, iterative forecasting model of methane ebullition rates in a small eutrophic reservoir. The results show that their refitting approach provides more accurate predictions of methane ebullition rates up to 2 weeks into the future, and it outperforms forecasts without refitting and a persistence null model. The study highlights the need for an improved mechanistic understanding of methane models and future improvements.

Robison et al. quantified stream diffusive methane emissions and compared them to previously published ebullitive emission rates in four lowland headwater streams to construct a complete methane emission budget. They measured the methane isotopic composition along with the sediment microbial community to investigate production and oxidation across the streams. They show that diffusive methane emissions are 78%–100% of total emissions, and methane oxidation depletes approximately half of the dissolved methane. The authors suggest a conceptual model of methane production, oxidation, and emission from small streams.

Vinogradova et al. investigated the transport of dissolved methane in the Eurasian continental slope and Siberian shelf break during ice melt. The research shows a patchy pattern of methane supersaturation and suggests that sea ice transports methane from the shelf. The study highlights the buffering capacity for seasonal storage of atmospheric and marine methane in the polar mixed layer. It also calculates the potential sea–air flux of methane and describes intrusions of methane plumes from the polar mixed layer into the cold halocline layer.

D'Ambrosio and Harrison critically reviewed 163 peer-reviewed studies that estimate diffusive methane fluxes from lake sediments using sediment incubations, benthic chambers, and modeling approaches. They summarized the advantages and limitations of each method and discussed published comparisons, and they also identified knowledge gaps in understanding lake methane dynamics.

To improve greenhouse gas emission estimates, Grinham et al. examined the methane potential of sediments in mesotrophic and eutrophic sub-tropical reservoirs under different nutrient and organic carbon availabilities. The study shows that these systems are carbon-limited, and the addition of organic carbon significantly increases anaerobic methanogenesis. A comprehensive catchment monitoring program revealed that the frequency of rainfall events is a critical driver of organic matter inputs that drive reservoir methane emissions in the sub-tropical region.

Lapham et al. investigated the effect of engineered aeration on methane dynamics in a eutrophic estuary in Rock Creek, Maryland. The experiment tested the hypotheses that bubble aeration enhances air–water methane flux, and the addition of oxygen will increase aerobic methane oxidation. The results show that regardless of the aeration status, the methane concentrations remained consistently high in all times and locations, establishing the sub-estuary as a source of methane to the atmosphere. The fine-bubble approach showed lower air–water methane fluxes compared to the larger bubble, destratification system.

Submerged macrophytes may affect gas exchange by reducing wind turbulence. Baliña et al. conducted a study in Argentina and revealed that clear vegetated lakes had higher mean annual methane partial pressure (pCH_4) despite having similar mean annual methane diffusive flux. Their results suggest that physical factors such as wind-induced turbulence control these differences in pCH_4 rather than biological factors. The findings indicate that submerged vegetation could dampen wind-induced turbulence and augment pCH_4 in surface waters.

Sherman and Ford presented methane emissions from Cotter Reservoir in Canberra, Australia, during a period of flooding following a long drought. The measurements spanned the first major flood events in 26 years. The floods resulted in hypolimnion warming and the introduction of large amounts of organic carbon. Average methane emissions prior to the flooding were low and uniform across the reservoir, but following the first floods, mean emissions increased dramatically and varied along the reservoir's axis. The authors attributed the changes in methane emissions to both the thermal enhancement of sediment methanogenesis and the supply of fresh organic matter.

In this study, Nijman et al. incubated methane-oxidizing bacteria (MOB) from sediments of four sub-tropical lakes to determine the effects of phosphorus (P) on MOB community composition and methane oxidation. The results show that increases in phosphate concentrations up to 10 μM significantly increased methane oxidation and bacterial biomass P content, while MOB community composition was not affected by phosphate. These effects only occurred at low phosphate concentrations, indicating that high nutrient loads may not mitigate the increased methane production.

Zimmermann et al. aimed to model methane-oxidizing bacteria diversity and niche partitioning based on differences in methane oxidation kinetics and temperature adaptation. The model approach closely reproduced diversity and niche preference patterns of methanotrophs observed in seasonally stratified lakes, but the combination of trait values resulting in coexisting methanotroph communities was limited to very confined regions. The study suggests that natural selection may drive trait values into the specific configurations observed in nature.

Bertolet et al. conducted sediment incubation experiments on 22 lakes to investigate whether variation in microbial community composition is related to the response of sediment methane production to increases in organic matter. The results show that sediment microbial community composition is significantly correlated with sediment methane production responses to organic matter additions. The diversity and richness of the non-methanogen community were found to be the most predictive metrics of the response.

Maier et al. investigated local CO_2 and methane concentrations in the Romanian part of the Danube Delta, determining horizontal gradients in dissolved gas concentrations. Delta-scale concentration patterns were stable across seasons, while small connecting channels were highly influenced by the riparian wetland. The study highlights the effect of plant-mediated gas transfer on dissolved gas concentrations and supports recent studies stressing the need to account for ebullitive gas exchange when assessing metabolism parameters from O_2 in shallow, productive settings.

In this study, genetic and geochemical analyses were used by van Grinsven et al. to investigate the drivers of the distributions, abundances, and community compositions of methane-oxidizing bacteria (MOB) across five lakes in central Switzerland. The results show that methanotrophic abundances peaked in sediments of an oligotrophic lake, and the trophic state at the time of sediment deposition was the best predictor of MOB community structure. Elevated methane fluxes combined with low MOB abundances in surface sediments of eutrophic lakes suggest that a major portion of sedimentary methane bypasses the biological methane filter and escapes to overlying water.

Valiente et al. used a set of chemical, hydrological, climate, and land-use parameters to predict biotic saturation of GHGs in boreal lakes. The predictions were based on surface water samples from 73 lakes in south-eastern Norway covering wide ranges in dissolved organic matter and nutrient concentrations, as well as catchment properties and land use. The study found that catchment characteristics such as lake size, precipitation, and terrestrial primary production in the watershed control the saturation of GHG in boreal lakes.

In a study of Teardrop Lake in Greenland, Cadieux et al. used stable isotope and 16S rRNA gene amplicon sequencing to determine water column carbon and hydrogen isotopes and microbial community composition. Methane isotopic values were highly enriched in carbon and hydrogen isotopes at 4 m depth, suggesting efficient methanotrophic communities. The researchers suggest that the methane cycling is decoupled from a traditional depth-dependent model, and understanding linkages between depth-dependent microbial dynamics and methane biogeochemistry is necessary to constrain the sensitivity of the methane cycle to future climate change.

Jensen et al. measured diffusive CO_2, methane, and N_2O fluxes from 20 agricultural reservoirs on seasonal and diel timescales. CO_2 concentrations were highest in spring and fall and lowest in mid-summer, while methane was highest in mid-summer, and N_2O was elevated in spring. CO_2 concentrations were affected by factors related to benthic respiration, while methane content was positively correlated with factors that favored methanogenesis, and N_2O concentrations were driven mainly by variation in reservoir mixing. The study estimated mean CO_2-eq flux during the open-water period, ranging from 5,520 to 10,445 mmol m^{-2} $year^{-1}$.

Martinez et al. conducted a stable isotope study to identify sources and sinks of methane in standing dead trees (snags) in freshwater forested wetlands. Their results suggest that snags could be important for methane emission and oxidation and may become more common in coastal areas as marshes migrate into freshwater forested wetlands. They found that methane emissions from snag stem sides and the soil–atmosphere interface were enriched in $\delta^{13}C$, which may point to methane oxidation when moving through the snags. The study highlights the need for further research on the relevance of snags for greenhouse gas cycling at regional and global scales.

Melack et al. evaluated the adequacy of available methane measurements, sampling and field methods, atmospheric measurements, and previously published fluxes and regional estimates to regionalize and constrain the variability of methane fluxes in the Amazon basin. They highlight the need to better understand biogeochemical and physical processes in the Amazon basin to improve mechanistic and statistical models. The authors recommend the application of new remote sensing techniques, increased sampling frequency and duration, experimental studies, and the development of appropriate models for hydrological and ecological conditions. They also suggest the use of advanced methods in microbial ecology and experimental manipulations to strengthen modeling efforts.

Bussman et al. investigated dissolved and atmospheric methane concentrations along 584 km of the Elbe River (Germany). Dissolved methane varied by almost 2.5 orders of magnitude with the hotspots in dissolved and atmospheric concentrations aligning with manmade structures, such as weirs, harbors, and groins. In addition, they compared emission estimates from discrete and continuous sampling approaches. They found that both are sufficient for upscaling methane emissions along rivers but concluded that regions with anthropogenic modifications should be considered in monitoring.

Einzmann et al. used a dual isotope technique to explore methane dynamics in a eutrophic lake in Germany. The stable carbon and hydrogen isotope composition revealed that methane sources and processing varied with stratification and lake depth. Methanogenic pathways differed spatially and seasonally between littoral and pelagic sites, while groundwater inputs of methane were more pronounced during the mixed period. During the stratified period, aerobic methane oxidation in the water column and sulfate-dependent anaerobic methane oxidation in the sediments helped to regulate methane reaching the epilimnion. This study clearly describes how a dual isotope approach of methane in various lake components can provide insight into lake methane dynamics.

Rabaey and Cotner measured GHGs during the ice-free season from 26 ponds in Minnesota (United States) to identify emission drivers from these small waterbodies that have been recognized as significant emitters despite their size. The ponds varied in terms of land use and included natural ones, but all were greenhouse gas sources with methane-dominating emissions. As seen previously, methane emissions positively correlated with phosphorus and anoxia, but in this study duckweed coverage was also a significant predictor with implications for the management of constructed ponds.

Thottathil et al. investigated the variability and controls of stable carbon isotopic fractionation during aerobic methane oxidation in temperate lakes. The authors used experimental incubations of unamended water samples from six temperate lakes at different depths and temperatures to better constrain the natural variability and controls of the isotopic fractionation factor (αox). They found that αox systematically increased from the surface to the deep layers, positively related to the abundance of methane oxidizing bacteria. The authors developed a general model predicting αox that ensures more realistic methane oxidation rates when applying stable carbon isotope-based quantification.

Eugster et al. investigated carbon emissions from an Arctic lake (Toolik Lake, Alaska, United States) using measurements of eddy covariance fluxes and continuous dissolved concentrations of methane and carbon dioxide. Future (30-year) projections suggest increasing soil temperatures will enhance carbon emissions, whereas increasing rainfall intensity will reduce them. The integrated use of eddy covariance and continuous dissolved concentrations allowed the resolution of highly resolved gas exchange coefficients to be compared with gas exchange models, which revealed that the approaches only converge at high wind speeds and that the gas exchange models underpredict true coefficients. The higher coefficients at low wind speeds are attributed to turbulence at the air–water interface being impacted by turbulence generated on land and may be characteristic of other lakes in similar environments.

Author contributions

All authors listed have made a substantial, direct, and intellectual contribution to the work and approved it for publication.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's note

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