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Short Communication

Lakes shifted from a carbon dioxide source to a sink over past two decades in China

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Lakes emit large amounts of carbon dioxide (CO_2) into the atmosphere with 0.81 Pg C a^{-1} [1], which offsets approximately 24% of global land carbon sink. However, there is considerable uncertainty in the estimate due to limited data and the effects of human activity and climate change. In China, lakes exhibit substantial variability in CO_2 exchange, resulting in uncertainties in national and regional land carbon sink assessments. For instance, on the Tibetan Plateau, lake-atmosphere CO_2 exchange can enhance land carbon sink by 33% or reduce it by 29% [2,3]. China's lakes have undergone widespread changes in the past decades; however, how they shift their role in CO_2 budget estimations over time remains unclear due to the shortage of time-series data.

China's lakes, with their diverse types and extensive distribution, hold global significance. These lakes are categorized into five groups [4]: East Plain lakes (EPL), Yunnan-Guizhou Plateau lakes (YGPL), Tibetan Plateau lakes (TPL), Inner Mongolia-Xinjiang lakes (IMXL), and Northeast Plain and Mountain lakes (NPML). However, global estimates of lake carbon emissions have predominantly relied on data from boreal (e.g., Finland) or northern temperature regions (e.g., the United States), lacking comprehensive information on China's lakes [5,6]. Notably, the CO_2 dynamics in lakes are closely associated with temperature, organic matter loads, and eutrophic status. These environmental variables in most of China's lakes exhibit distinct characteristics compared with those in boreal or northern temperate regions. Ignoring these differences poses a challenge in estimating the CO_2 budget in global lakes.

A number of studies have attempted to estimate CO_2 emissions from China's lakes in the past two decades to fill the data gaps [3,7]. The results showed that China's lakes are significant CO_2 sources, with a wide range of uncertainty (7.3 to 16 Tg C a^{-1}). However, these findings have been challenged by regional observations indicating CO_2 uptake [2,8]. While existing literature focuses on emission magnitudes using limited data from different periods [3,7], investigations into the underlying mechanisms remain scarce. Human activities and climate change have led to a considerable increase in algal blooms in China's lakes [9], alongside changes in lake size and number due to glacier melt and rainfall runoff [10,11]. Simultaneously, a decreasing external loading accompanied by increasing dissolved oxygen has been widely reported [12]. A poor understanding of how CO_2 responds to these changes may lead to large uncertainty in emissions estimation and preclude the accurate prediction of variability under a changing environment.

Whether China's lakes act as CO_2 sinks or sources and their changes over time remain elusive. In this short communication, we took advantage of two comprehensive national surveys of CO_2 partial pressure (pCO_2) conducted during 1988–1992 and 2007–2010 to address this issue, and the CO_2 emissions are determined by pCO_2. By determining CO_2 emissions based on pCO_2 measurements, we compared the pCO_2 and CO_2 emissions between the two periods using an exceptionally extensive dataset. This approach allowed us to examine the relationship between these changes and environmental variables.

In total, 282 lakes were surveyed in 1988–1992 and 234 lakes in 2007–2010. The pCO_2 varied significantly across zones and between the two periods (Fig. 1), aligning with previous global lake studies [5]. Highly variable pCO_2 generally occurred in the EPL and TPL with numerous lakes, and peak pCO_2 occurred in the NPML. Over time, the average pCO_2 decreased by half, from 709 ± 691 to 332 ± 362 μatm (1 μatm = 0.1 Pa; Table S1 online). The 150 lakes surveyed in both periods showed a consistent decreasing trend in pCO_2 (Fig. 1d). Zonal CO_2 was unrelated (p > 0.05) to temperature and precipitation. However, differences in CO_2 were well explained

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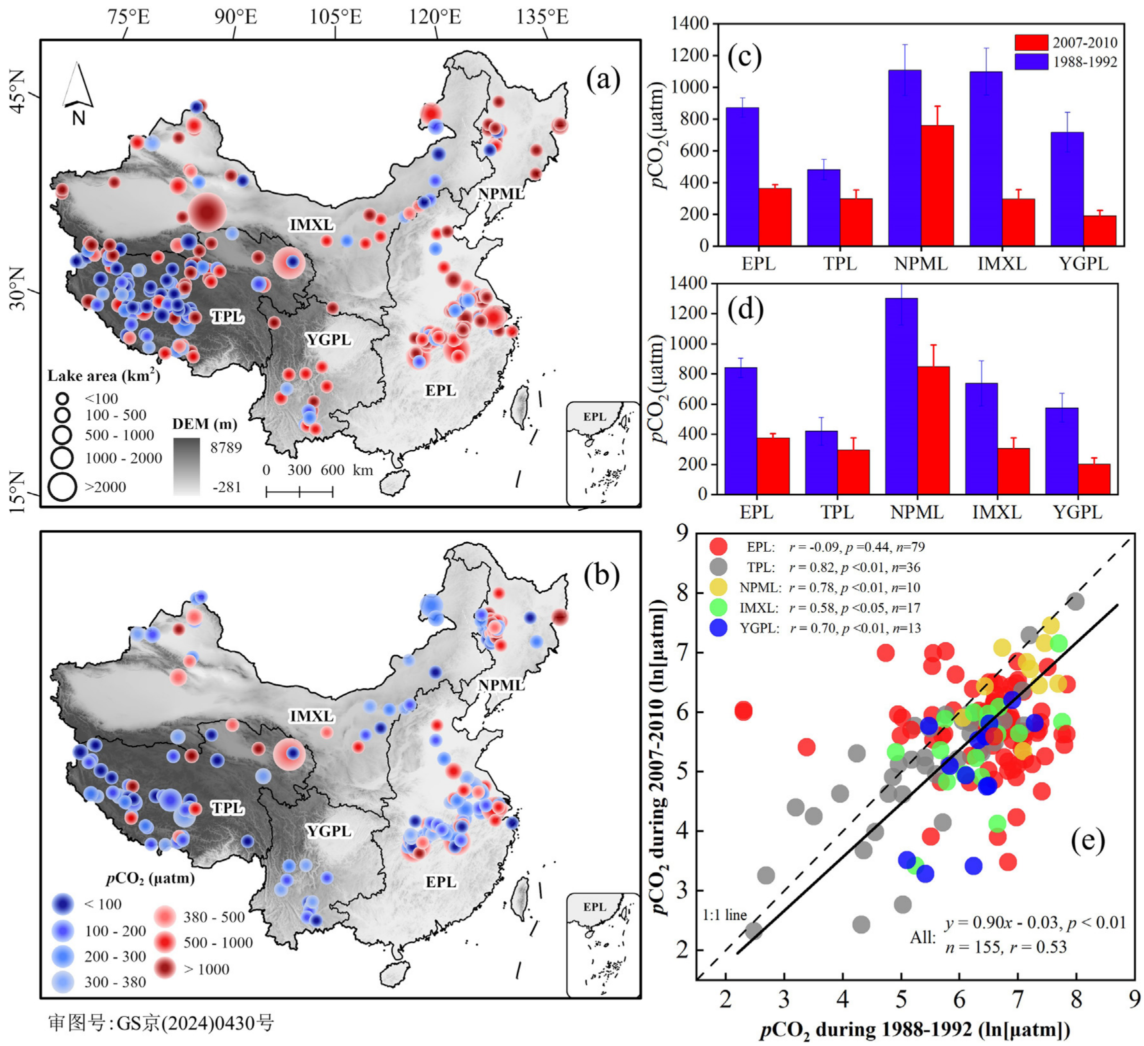

Fig. 1. Spatial distribution and zonal comparison of pCO_2 in China's lakes. (a) Spatial distribution of pCO_2 during 1988–1992; (b) spatial distribution of pCO_2 during 2007–2010; (c) the pCO_2 comparison across five zones which were measured during 1988–1992 and 2007–2010; (d) the pCO_2 comparison in lakes which were both sampled for CO_2 measurement in the two periods (1988–1992 versus 2007–2010); and (e) the relationship of lake pCO_2 between the two periods. Error bars indicate standard error.

by the soil organic carbon (SOC) and chemical oxygen demand (COD) loadings in the watershed (Fig. S1 online). This suggests that external loadings (e.g., dissolved organic carbon, DOC) input may drive CO_2 variability by providing substances [13].

The CO_2 emissions decreased from 12.75 ± 2 3.05 mmol m^{-2} d^{-1} in 1988–1992 to −2.02 ± 12.30 mmol m^{-2} d^{-1} in 2007–2010 (Table S1 online), indicating a source-to-sink shift of China's lakes. We estimated that China's lakes emitted 2.748 Tg C a^{-1} (25th–75th percentiles: 1.346–4.138 Tg C a^{-1}) during 1988–1992 (Fig. 2). Among the total CO_2 efflux, 1.430 Tg C a^{-1} (25th–75th percentiles: 1.319–1.539 Tg C a^{-1}) came from the EPL (Table S2 online), contributing 52% of the lake emissions. During 2007–2010, the CO_2 flux was −0.408 Tg C a^{-1} (25th–75th percentiles: −1.408–0.605 Tg C a^{-1}), with 80% of the influx occurring in the EPL and TPL. This shift is advocated by a recent field measurement that reported a few lakes being a significant CO_2 sink [2,8].

Lake CO_2 dynamics are related to inter-connected physical, chemical, and biological mechanisms associated with human activities and climate change. To differentiate the effects of environmental variables and quantify their contributions to CO_2 variability, we categorized these lakes into three types (DOC-rich lakes, eutrophic lakes, and endorheic lakes, Fig. 2) based on gradients in climate, organic carbon, and eutrophic status [3,4,12]. Our results demonstrated that the variability of lake CO_2 can be primarily attributed to chemical production in the NPML (DOC-rich lakes), biological consumption in the EPL and YGPL (eutrophic lakes), and physical dilution in the TPL and IMXL (endorheic lakes) based on the correlations between CO_2 and environmental variables (Table S3 online).

In the NPML (DOC-rich lakes), we observed peak lake DOC levels (Fig. S2 online) and a positive correlation between CO_2 and DOC (Table S3 online). This suggests that the decomposition of organic carbon is the primary driver of CO_2 emissions. It is estimated that the external carbon loading (represented by COD) decreased by 15% while nutrient loadings (e.g., NH_4^+-N) declined by 13% [12]. These reductions were accompanied by corresponded a 56% decline in CO_2 emissions (Fig. 2). In eutrophic lakes at the EPL and YGPL, characterized by high chlorophyll *a* (Chl-*a*), CO_2 showed no correlation with DOC but exhibited a negative relationship with Chl-*a* (Table S3 online), suggesting that eutrophication can reduce CO_2 emissions by stimulating primary production. Over the past decades, phytoplankton abundance in these lakes has significantly increased, with Chl-*a* concentration rising by 83% and cyanobacteria increasing by 92% [9]. The rising cyanobacteria and Chl-*a*

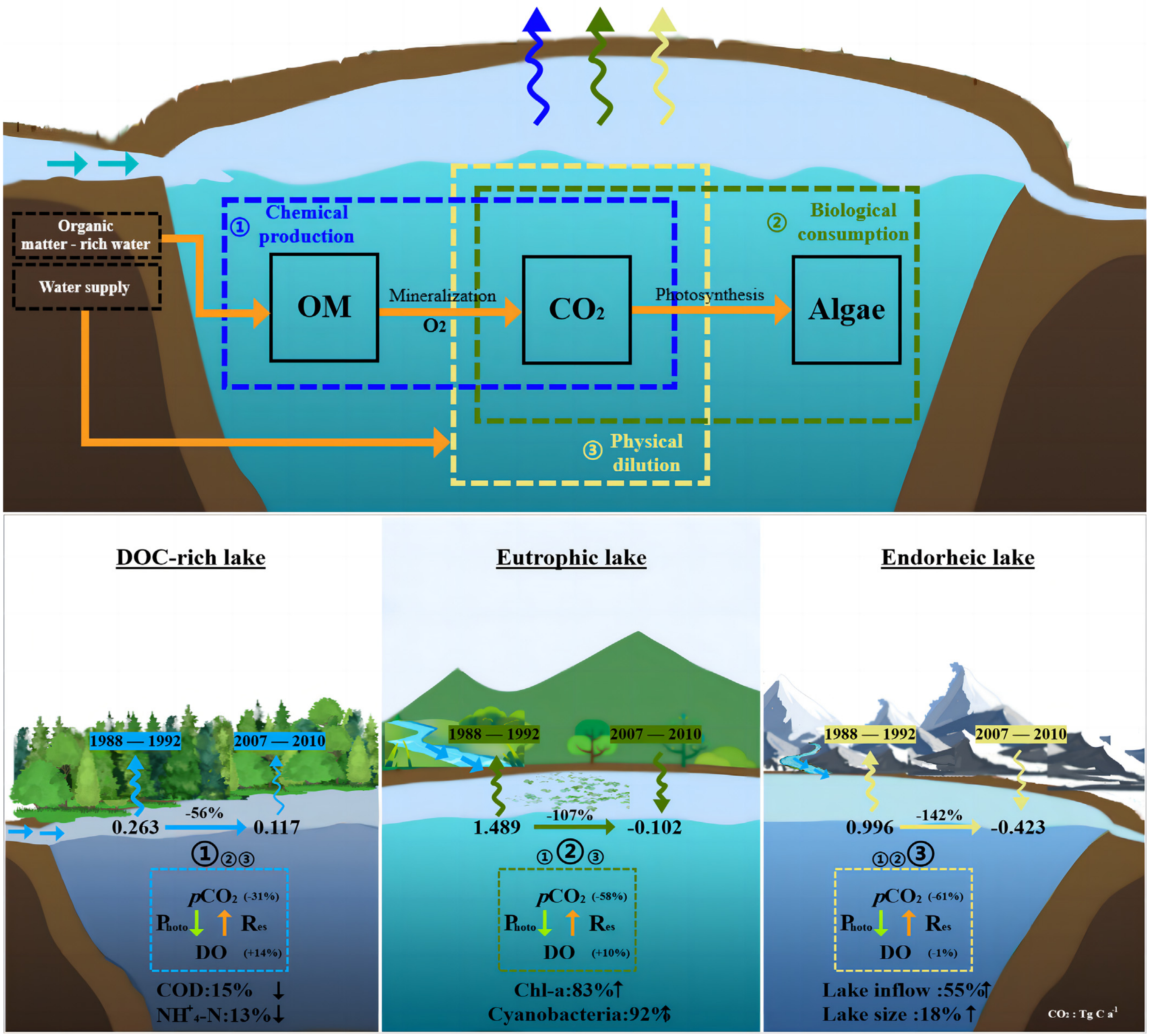

Fig. 2. Schematic of the CO_2 budget (Tg C a^{-1}) in China's lakes for the studied periods (1988–1992 versus 2007–2010). The five zones were clustered into eutrophic lakes (EPL and YGPL), DOC-rich lakes (NPML), and endorheic lakes (TPL and IMXL) based on eutrophication, hydrological condition, and watershed-derived DOC input. The P_{hoto} is photosynthesis, which is represented by green arrows (consume CO_2 and increase O_2). The R_{es} is respiration, which is represented by orange arrows (consume O_2 and increase CO_2) in the lakes.

confirmed that the enhanced algal-induced primary production has led to a shift in these lakes from being CO_2 sources to becoming CO_2 sinks.

In the endorheic basin lakes (TPL and IMXL), characterized by low temperatures and relatively sparse population [4], the decrease in CO_2 emissions may be attributed to climate change-induced lake expansion [11]. Previous studies have shown that increased precipitation has contributed to a rising trend in the number and size of lakes [11]. Meanwhile, air temperature increased significantly (Fig. S3 online), likely leading to the expansion of lake areas due to melting snow and glaciers. Lakes that expand due to precipitation in glacierized catchments or glacier-fed lakes generally receive fewer terrestrial organic inputs for CO_2 production and are typically under-saturated in CO_2 [14], leading to a dilution effect on CO_2 concentrations. Lakes in the endorheic basin typically have high levels of dissolved inorganic carbon [3], and increased runoff may transport more calcium ions, which can enhance CO_2 uptake. Our estimation indicates that a 55% increase in lake inflow and an 18% increase in lake size resulted in a 142% decrease in CO_2 emissions from these lakes, effectively shifting them from CO_2 sources to sinks (Fig. 2).

Dissolved oxygen (DO) serves as a reliable indicator of CO_2 variability, although the underlying mechanisms vary geographically. The negative correlation between CO_2 and DO (Fig. S4 online) can be attributed to either respiration, where oxygen is consumed and CO_2 is produced, or photosynthesis, where CO_2 is fixed and oxygen is produced. The significant relationship between CO_2 and DOC in NPML (Fig. S4 online) suggested that organic matter degradation dominates the DO levels. However, in eutrophic lakes at the EPL and YGPL, the CO_2 levels were unrelated to DOC (Table S3 online), while a positive correlation between DO and Chl-*a* (Fig. S5 online) was observed. This indicates that the relationship may be driven by primary production, as increased algae-induced primary production can lead to a decrease in CO_2 and an increase in DO. The increase in DO concentration in China's inland water has been reported [12]. In this context, the DO levels also significantly increased due to high primary production in eutrophic lakes and declining external loadings in DOC-rich lakes (Fig. 2). These factors likely contribute to the decline in CO_2 emissions.

Our results provide evidence that anthropogenic and natural factors concurrently regulate the CO_2 variability of lakes on a national scale. The impact of eutrophication on CO_2 variability is evident from its strong correlation with Chl-*a* and DO levels (Table S3 and Fig. S4 online). While the intensive degradation of organic matter contributes to substantial CO_2 emissions from lakes in the NPML [13], the reduction in human-derived external loadings [12] likely contributes to the decrease in CO_2 efflux. The impacts of natural factors and climate change on CO_2 variability are via two mechanisms. Firstly, climate warming has increased primary production in lakes, leading to lower CO_2 levels. Secondly, the lakes in the cold TPL region are highly sensitive to temperature; therefore, climate warming might have substantially enhanced the CO_2 variability. Overall, our findings highlight the complex interplay between anthropogenic and natural factors, as well as the influence of climate change, in shaping the CO_2 dynamics of lakes.

The source-to-sink shift of China's lakes has three implications. First, the primary CO_2 uptake occurred predominantly in lakes experiencing algal blooms, which differs from previous studies [3]. This highlights the significance of accurately estimating the CO_2 budget by considering diverse lake types [1]. Second, the significant difference in CO_2 levels observed between the two periods underscores the importance of long-term sampling to improve the quantification of CO_2 emissions. Last, our findings demonstrate that DO is the best predictor of CO_2 variability. A recent survey with long-term measurements revealed increasing DO concentrations in eutrophic lakes due to high primary production [15], suggesting that eutrophic lakes can act as CO_2 sinks within the terrestrial biosphere.

Our study revealed a significant shift in China's lakes, leading to substantial changes in the CO_2 budget, as evidenced by a halving of pCO_2. This shift can be primarily attributed to increased primary production in eutrophic lakes, reduced external carbon loadings in organic carbon-rich lakes, and expanded water volume in endorheic lakes. This transition on a nationwide scale highlights the importance of considering multiple mechanisms when assessing CO_2 flux in lakes. It underscores the need for comprehensive investigations of various environmental changes to accurately understand CO_2 dynamics in lakes. Furthermore, lake CO_2 dynamic variabilities are related to the size, eutrophic status, and saline of the lakes. Given the global significance of China's lakes and their diverse types, it is crucial to gather more detailed lake datasets, including saline lakes and eutrophic lakes, to improve the accuracy of CO_2 budget estimations. Additionally, the CO_2 emissions were calculated from the pCO_2, which may bias the emissions due to the limitations and uncertainties of snapshot sampling and the pCO_2 measurements, and more direct measurements with temporally representative are also needed to accurately estimate the emissions. In conclusion, our findings shed light on the complex interplay of factors affecting CO_2 dynamics in China's lakes, highlighting the need for comprehensive data and a nuanced understanding of these ecosystems to accurately assess their contributions to the carbon cycle.

Conflict of interest

The authors declare that they have no conflict of interest.

Acknowledgments

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Author contributions

Qitao Xiao designed and conceptualized the study, performed data analysis, and wrote the original manuscript. Xiaofeng Xu performed data analysis and edited the manuscript. Tianci Qi and Juhua Luo prepared the figures and participated in data curation. Xuhui Lee reviewed the manuscript and provided guidance. Hongtao Duan designed and conceptualized the study, and edited the manuscript.

Appendix A. Supplementary materials

Supplementary materials to this short communication can be found online at https://doi.org/10.1016/j.scib.2024.03.022.

References

[1] DelSontro T, Beaulieu JJ, Downing JA. Greenhouse gas emissions from lakes and impoundments: Upscaling in the face of global change. Limnol Oceanogr Lett 2018;3:64–75.
[2] Li X-Y, Shi F-Z, Ma Y-J, et al. Significant winter CO_2 uptake by saline lakes on the Qinghai-Tibet Plateau. Glob Change Biol 2022;28:2041–52.
[3] Li S, Bush RT, Santos IR, et al. Large greenhouse gases emissions from China's lakes and reservoirs. Water Res 2018;147:13–24.
[4] Zhang G, Yao T, Chen W, et al. Regional differences of lake evolution across China during 1960s–2015 and its natural and anthropogenic causes. Remote Sens Environ 2019;221:386–404.
[5] Raymond PA, Hartmann J, Lauerwald R, et al. Global carbon dioxide emissions from inland waters. Nature 2013;503:355–9.
[6] Holgerson MA, Raymond PA. Large contribution to inland water CO_2 and CH_4 emissions from very small ponds. Nat Geosci 2016;9:222–6.
[7] Ran L, Butman DE, Battin TJ, et al. Substantial decrease in CO_2 emissions from Chinese inland waters due to global change. Nat Commun 2021;12:1730.
[8] Jia J, Sun K, Lü S, et al. Determining whether Qinghai-Tibet Plateau waterbodies have acted like carbon sinks or sources over the past 20 years. Sci Bull 2022;67:2345–57.
[9] Su H, Chen J, Li Y, et al. Carp stocking and climate change are potentially more important factors than nutrient enrichment driving water quality deterioration in subtropical freshwater lakes in China. Limnol Oceanogr 2023;68:S131–43.
[10] Zhou J, Wang L, Zhong X, et al. Quantifying the major drivers for the expanding lakes in the interior Tibetan Plateau. Sci Bull 2022;67:474–8.
[11] Zhang G, Luo W, Chen W, et al. A robust but variable lake expansion on the Tibetan Plateau. Scie Bull 2019;64:1306–9.
[12] Ma T, Zhao N, Ni Y, et al. China's improving inland surface water quality since 2003. Sci Adv 2020;6:eaau3798.
[13] Maberly SC, Barker PA, Stott AW, et al. Catchment productivity controls CO_2 emissions from lakes. Nat Clim Chang 2013;3:391–4.
[14] St Pierre KA, St Louis VL, Schiff SL, et al. Proglacial freshwaters are significant and previously unrecognized sinks of atmospheric CO_2. Proc Natl Acad Sci USA 2019;116:17690–5.
[15] Jane SF, Hansen GJA, Kraemer BM, et al. Widespread deoxygenation of temperate lakes. Nature 2021;594:66–70.

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