N₂O saturation level (%N₂O) versus dissolved inorganic nitrogen (DIN=NO₃⁻ + NH₄⁺), oxygen saturation level (%O₂), relative abundance of NO₃⁻ (%NO₃⁻ =NO₃⁻ / (NO₃⁻ + NH₄⁺) x 100), relative abundance of NH₄⁺ (% NH₄⁺ =NH₄⁺ / (NO₃⁻ + NH₄⁺) x 100), primary production, chlorophyll-a (Chl-a) concentration, dissolved organic carbon (DOC) and colored dissolved organic matter slope ratio (CDOM SR) in several African tropical lakes. Horizontal dotted line indicates saturation with the atmosphere, and solid lines are fitted to the data (Table S3). Humic Lake Mai Ndombe had a high DIN concentration associated with high %N₂O, while hypersaline lake Nyamunuka had even higher DIN but nearly no N₂O due to strong denitrification related to the nearly anoxic water column. For non-humic lakes, the positive relation between %N₂O with the relative abundance of NO₃⁻ (%NO₃⁻) and the negative relation with the relative abundance of NH₄⁺ (%NH₄⁺) confirm the hypothesis of N₂O removal by denitrification in low %NO₃⁻ lakes, and N₂O production by nitrification in high %NO₃⁻ lakes.

Fig. S1.
Fig. S2.

Examples of vertical profiles of CH$_4$ concentration and oxygen saturation level (%O$_2$) in Lakes Victoria, Tanganyika, Kivu and Edward. Lakes Tanganyika and Kivu are permanently stratified (meromictic) where anoxic bottom water is a permanent feature. Lakes Victoria and Edward are seasonally stratified (holomictic) anoxic bottom water only occurs seasonally (Fig. S3). The meromictic nature sustains a constant upward flux of CH$_4$ from bottom to surface waters, and methane oxidation (MOX) in surface waters might be limited by sunlight ($\text{22}$) in Lakes Tanganyika and Kivu characterized by deeper photic depths. In the holomictic lakes such as Victoria and Edward, the seasonal mixing led to full oxygenation to bottom waters and strong CH$_4$ removal by MOX, preventing the accumulation of extremely large quantities of CH$_4$ in anoxic bottom waters during the stratified period, as observed in the meromictic lakes (Fig. S3). Note that Lake Kivu is characterized by higher CH$_4$ concentrations in the hypolimnion than Lake Tanganyika, which might explain higher CH$_4$ concentrations in surface waters in Lake Kivu than in Lake Tanganyika at similar bottom depth (Fig. 4).
Fig. S3.
Examples of vertical profiles of CH$_4$ concentration, oxygen saturation level (%O$_2$) and water temperature in holomictic Lakes Victoria and Edward, during contrasting periods of the year (vertically mixed and stratified).
Fig. S4.

Conceptual diagram summarizing the processes that increase or decrease CO$_2$ in surface waters of lakes as a function of lake size (surface area and depth). The CO$_2$ content in surface waters of lakes results from the balance of sources and sinks of CO$_2$ that are in part linked to organic carbon processing within the lake (metabolic status at ecosystem scale, that is, the balance between gross primary production (P) and ecosystem respiration (R)) (76), in part linked to hydrological inputs of CO$_2$ from rivers, surface runoff, soil-water and ground-water (77,78), and in part related to the exchange of CO$_2$ with the atmosphere. Part of the heterotrophic degradation of organic matter (leading to the production of CO$_2$ and contributing to R) is sustained by allochthonous inputs of dissolved (DOC) and particulate (POC) organic carbon from the catchment and riparian wetlands (15). The relative intensity of external inputs of

---

**Processes increasing CO$_2$**

- Hydrological inputs of dissolved CO$_2$ from rivers, ground-water, soil-water, wetlands
- Inputs of allochthonous organic carbon sustaining pelagic and benthic R
- Decoupling of epilimnion from hypolimnion

**Processes decreasing CO$_2$**

- Increase of $k$
- P (high CDOM)
- P (low CDOM)

**Processes favoring CO$_2$ equilibrium with the atmosphere**

- Decoupling of epilimnion from hypolimnion
- Increase of $k$

**Resulting lake surface CO$_2$ content**

- Humic lakes
- Non-humic lakes

---

**Lake surface area**

**Lake mean depth**

- Small lake
- Shallow lake
- Littoral zone
- Large lake
- Deep lake
- Pelagic zone
DOC, POC and CO₂ depend on a complex combination of land cover on the catchment, catchment slope, lake size and precipitation (15). Inputs of DOC and humic content are strongly promoted by the presence of riparian wetlands on the catchment (79). The relative importance of internal processing of allochthonous organic carbon inputs depends on water residence time that is itself a function of the fraction of hydrologic export as evaporation (80) and scale with lake size. Overall, most processes affecting CO₂ dynamics in lakes directly or indirectly scale with lake size, leading to documented inter-lake variations as function of lake average depth and lake surface area (8,14,15,25,26,81), and intra-lake variations as a function of bathymetry, from the shallow (littoral) to deeper (pelagic) zones. Small lakes have a greater connectivity and potential exchange of organic and inorganic carbon with the riparian wetlands and surrounding terrestrial landscape along its periphery relative to lake surface area than large lakes. Hence, hydrological inputs of CO₂ (I) and organic matter (II) should be relatively higher in smaller lakes than in larger lakes (15,81). The fraction of organic matter that is mineralized within a lake or that is on the contrary exported depends on hydrologic residence time that is function of the ratio of water loss by evaporation to river outflow, that itself scales with the ratio of watershed area to lake area (80) or possibly also slope of the catchment (82). The relative contribution of CO₂ hydrologic inputs to CO₂ generated by organic matter degradation strongly declines with increasing water residence time (80). In general, larger and/or deeper lakes tend to have longer water residence times than smaller ones. Similarly, allochthonous inputs of nutrients should decline with increasing lake area and water depth, hence P should be higher in smaller/shallower lakes than larger/deeper lakes (V and VI) (15,81). Planktonic and benthic P will also be modulated by the content of colored dissolved organic matter (CDOM) that reduces light availability in the water column, decreasing P (12). Vertical water column density stratification (physical stability) increases with maximum depth of the lake (83). This will promote the decrease of CO₂ in the mixed layer and the increase of CO₂ in bottom waters due to the decoupling of CO₂ uptake in surface waters by phytoplankton carbon fixation and CO₂ release in bottom waters due to degradation of organic matter by microbes (mineralization) following the sedimentation of organic matter particles to depth (III). Higher water column stability also results in reduced upward turbulent flux of CO₂. Increasing lake size leads to an increase in fetch and enhanced turbulence generated by wind shear (16). This has two consequences: deeper mixed layers (83) and higher gas transfer velocities (k) (16) both promoting the equilibration of gases with the atmosphere (IV). Precipitation or dissolution of calcium carbonate leads, respectively, to a production or consumption of CO₂ (2HCO₃⁻ + Ca²⁺ = CaCO₃ + CO₂ + H₂O) although this process usually contributes marginally to changes in CO₂ content in surface lakes (55). CO₂ is in chemical equilibrium with HCO₃⁻ and CO₃²⁻ (CO₂ + H₂O = HCO₃⁻ + H⁺ = CO₃²⁻ + 2H⁺) and the higher the HCO₃⁻ and CO₃²⁻ content of water (hardness) the higher the buffering capacity (relative change of CO₂ concentration to a dissolved inorganic carbon (DIC) change in response to a biogeochemical uptake or release) (e.g. 84). The left-hand side of the figure shows the processes that change CO₂ content and how their intensity changes with lake depth (between lakes or within a given lake) and/or lake surface area; the right hand-side of the figure shows the putative combination of processes that could explain the patterns observed in the sampled African lakes (Fig. 2). The “+” symbol indicates the processes we hypothesize as most important in regulating the observed patterns in African lakes. The “?” indicates that we could not determine a tendency based on available data (positive, negative or none at all).
Fig. S5.

Conceptual diagram summarizing the processes that increase or decrease CH$_4$ in surface waters of lakes as a function of lake size (surface area and depth). The dissolved CH$_4$ concentration in surface waters of lakes results from the balance of sources and sinks of CH$_4$. CH$_4$ is mainly produced by...
methanogenesis in sediments; CH$_4$ production in aerobic conditions related to phytoplankton metabolism has been shown to occur in African lakes although a marginal source compared to sedimentary sources (22). CH$_4$ produced in sediments can diffuse directly into the overlying water column, or accumulate as gas bubbles that can be released into the overlying water column (ebullition). Bubbles can reach the atmosphere or dissolve as they rise in water (partly or completely). The main processes that remove dissolved CH$_4$ in lakes are the emission of CH$_4$ to the atmosphere and the microbial CH$_4$ oxidation (MOX) either in oxic or anoxic conditions, at the sediment-water interface or in the water column. As for CO$_2$, hydrological inputs of CH$_4$ from rivers, surface runoff, soil-water and ground-water can contribute to CH$_4$ content in lakes (I) (85), although CH$_4$ is usually attributed mostly to internal production (14). The inputs of allochthonous (II) and autochthonous (III) organic matter to sediments stimulates sedimentary methanogenesis (86). This input of organic matter is higher in littoral zones of lakes than in deeper zones of lakes, as in small compared to larger lakes (87). Shallow water column also reduces the impact of CH$_4$ removal by MOX (IV), while the deepening of the mixed layer depth (VII) enhances the relative impact of MOX in CH$_4$ removal (88). Small lakes have a greater connectivity and potential exchange of organic matter and CH$_4$ with the riparian wetlands and surrounding terrestrial landscape along its periphery relative to lake surface area than large lakes. Shallower depths are favorable to methane ebullition (lower hydrostatic pressure countering release of bubbles), and the partial dissolution of rising bubbles will increase dissolved CH$_4$ concentration in surface waters (87). Additionally, small and shallow lakes can have higher production of phytoplankton or macrophytes supplying organic carbon to sediments and sustaining CH$_4$ production (89,90). Some of the CH$_4$ in the water column in the more central part of lakes is transported horizontally from hot-spot production littoral zones (91,92) although the importance of this process decreases with the size of the lake (V). The increase of lake depth leads to enhanced stratification (83) and the decoupling of the hypolimnion where CH$_4$ diffusing from the sediment accumulates and the epilimnion where CH$_4$ decreases due to loss to the atmosphere or to removal by aerobic MOX (VI, VII). The increasing lake size leads to an increase in fetch and enhanced turbulence generated by wind shear, and higher gas transfer velocity ($k$) values (16) promoting the equilibration of gases with the atmosphere (VIII). The left-hand side of the figure shows the processes that change CH$_4$ content and how their intensity changes with lake depth (between lakes or within a given lake) and/or lake surface area, the right hand-side of the figure shows the putative combination of processes that can explain the patterns observed in the sampled African lakes (Fig. 2). The “+” symbol indicates the processes we hypothesize as most important in regulating the observed patterns in African lakes.
Conceptual diagram summarizing the processes that increase or decrease N\textsubscript{2}O in surface waters of lakes as a function of lake size (surface area and depth). N\textsubscript{2}O can be produced as a byproduct of nitrification (oxidation of NH\textsubscript{4}\textsuperscript{+} to NO\textsubscript{3}\textsuperscript{−} in aerobic conditions). N\textsubscript{2}O is also involved in the last step (reduction of NO\textsubscript{3}\textsuperscript{−} to N\textsubscript{2} in anaerobic conditions), so N\textsubscript{2}O can accumulate in the case of incomplete reduction to N\textsubscript{2} (in presence of trace levels of O\textsubscript{2}) or, alternatively, be removed by denitrifiers (in low NO\textsubscript{3}\textsuperscript{−} conditions). The yield of N\textsubscript{2}O produced by nitrification strongly increases with decreasing oxygen levels. Denitrification can occur in presence of trace levels of O\textsubscript{2} (<6 µmol L\textsuperscript{−1}), but in this case there is an inhibition of reduction to N\textsubscript{2} step and N\textsubscript{2}O strongly accumulates. Hence, N\textsubscript{2}O production (from nitrification or denitrification) tends to be highest from both processes at low O\textsubscript{2} levels, while strictly anoxic conditions promote the removal of N\textsubscript{2}O by denitrification (reduction to N\textsubscript{2}). Rates of nitrification and denitrification (and N\textsubscript{2}O levels) increase with the levels of dissolved inorganic nitrogen (DIN) (50,93,94). Terrestrial DIN, dissolved (DON) and particulate (PON) organic nitrogen inputs stimulate N\textsubscript{2}O production that should be higher in smaller lakes (I) (as for DOC and POC, see Fig. S4). In humic lakes, phytoplankton production is low but microbial mineralization of organic matter is high and can lead to relatively high levels of DIN (23). In larger or deeper lakes, a strong
stratification (83) will promote a more marked oxycline and a peak of N₂O related to nitrification (95) (II). If the hypolimnion becomes anoxic, N₂O can decrease due to denitrification (88,95). The equilibrium of N₂O with the atmosphere will be favored in larger lakes due to the deepening of the mixed layer, as well as the increase in the gas transfer velocity (k) (III, IV) (16,83). In shallower lakes, the impact of fluxes between the sediment and the water column will be strongest. In the sampled lakes, sedimentary denitrification is the most likely explanation for the water column under-saturation of N₂O (V) (refer to Fig. S9) although this has only been occasionally reported in boreal lakes that are strongly over-saturated in N₂O (50). The left-hand side of the figure shows the processes that change N₂O content and how their intensity changes with lake depth (between lakes or within a given lake) and/or lake surface area, the right hand-side of the figure shows the putative combination of processes that could explain the patterns observed in the sampled African lakes (Fig. 2). The “+” symbol indicates the processes we hypothesize as most important in regulating the observed patterns in African lakes. The observed patterns of CO₂, CH₄ and N₂O are to some extent linked in the sampled non-humic lakes. Higher phytoplankton biomass in shallower lakes (littoral zones) leads to low CO₂ levels in surface waters, but also enhanced transfer of organic matter to sediments, consequently higher sedimentary organic matter degradation including methanogenesis possibly explaining the positive relationship between CH₄ dissolved concentration and chlorophyll-a (Chl-a) concentration (Fig. 6). The higher sediment denitrification (and uptake of N₂O from the water by the sediment) related to higher delivery of phytoplankton biomass to sediments might also explain the negative relationship between N₂O saturation levels and Chl-a (Fig. S1). The “?” indicates that we could not determine a tendency based on available data (positive, negative or none at all).
Dissolved CO$_2$ concentration versus HCO$_3^-$ concentration in several African tropical lakes. The concentration of CO$_2$ did not show clear patterns with the concentration of HCO$_3^-$ despite very large range of variation of both quantities. The two lakes with the highest CO$_2$ concentrations were located in the Congo River basin characterized by low rock weathering (17), hence, also characterized by the lowest HCO$_3^-$ concentrations (Mai Ndombe, Tumba). The highest HCO$_3^-$ concentrations were observed in the two hypersaline lakes (Nyamunuka and Kitagata). If the four humic lakes and the two hypersaline lakes are excluded, then CO$_2$ and HCO$_3^-$ concentrations are positively correlated for the remaining 12 lakes. It is unclear if such a correlation implies a causality or is simply spurious. Yet, such a positive relationship is inconsistent with the hypothesis that CO$_2$ under-saturation in lakes is driven by high HCO$_3^-$ and pH in hard-water lakes by opposition with soft-water lakes (77,96). In the sampled African lakes, CO$_2$ values above equilibrium were observed for Chlorophyll-a (Chl-a) concentrations below 11 µg L$^{-1}$, while CO$_2$ below equilibrium were observed for Chl-a above 17 µg L$^{-1}$. Solid line is the fit to the data (Table S3).
Fig. S8.

Surface partial pressure of CO$_2$ (pCO$_2$) versus dense forest cover and vegetation biomass on the catchment in several African tropical lakes. Vegetation biomass was extracted from pantropical national level carbon stock data-set (97), and dense forest cover from Global Land Cover 2000 database of Africa (98), using catchment delineation based on HydroSHEDS (65).
Sedimentary air-water diffusive CH$_4$ flux (22) versus primary production (P) and surface water chlorophyll-a (Chl-a) concentration in Lakes Edward, George and Nyamusingere. During the same incubations, a flux of N$_2$O from the water to the sediment was measured of -1.3 µmol m$^{-2}$ d$^{-1}$ in L. Edward, -0.7 µmol m$^{-2}$ d$^{-1}$ in L. George, and -4.0 µmol m$^{-2}$ d$^{-1}$ in L. Nyamusingere. While a negative flux is indicative of the removal of N$_2$O from the water column from sedimentary denitrification, no correlation was found with P nor Chl-a, indicating a more complex relation between sedimentary N$_2$O removal and organic matter delivery to the sediment.
Fig. S10.

Ebullitive air-water flux of CH$_4$ ($F_{\text{CH}_4}$) in African lakes (this study, Table S5), Pantanal lakes (99), Amazon floodplain lakes (100-103), Orinoco floodplain lakes (104), and one lake in India (105).
Fig. S11.

Difference of the partial pressure of CO$_2$ in surface waters (ΔpCO$_2$) and coefficient of variation (CV) of pCO$_2$ in surface waters between dusk and dawn (next day) as a function of chlorophyll-a (Chl-a) concentration in Lake Victoria during three cruises (Table S7). Sampling was carried out during daytime (dawn to dusk) and the ship anchored during the night. The difference between dusk and dawn (at the anchoring point) provides an estimate of the maximum daily amplitude. Solid line is fitted to the data (Table S3). The ΔpCO$_2$ values ranged between -63 and 983 ppm, with a median of 123 ppm and only in 2 cases out of 18 did the sign of the ΔpCO$_2$ (direction of FCO$_2$) change. These differences were consistent with diel variations of P and R and seemed to be related to phytoplankton biomass as indicated by the lower plot.
Fig. S12.

Diel variations of the partial pressure of CO$_2$ ($p$CO$_2$) in surface waters, wind speed and air-water CO$_2$ flux ($F$CO$_2$) in Lake Kivu (23/03/2007 (13:00) to 24/03/2007 (14:00), 60 min acquisition) and Lake Edward (20/01/2018 (18:00) to 22/01/2018 (15:00), 10 min acquisition). Grey horizontal dotted line indicates the day-time average, black horizontal dotted line indicates the night-time average.
Day-time and night-time averages of wind speed and gas transfer velocity \((k)\) computed with the parameterization of (64) in Lakes Victoria (Buzika Island, 29/01/2018 to 27/11/2018), Tanganyika (Kigoma, 28/02/2002 to 29/09/2006), Kivu (Bukavu, 01/01/2003 to 31/12/2011), and Lake Edward (Mweya, 22/03/2017 to 04/02/2018). These plots provide information on the wind speed variability at the measurement site, and do not necessarily represent absolute differences among the four lakes. Wind speed was higher during day-time because wind is in part forced by the gradient of air temperature between the lake surface and the surrounding land that is stronger during day-time.
Difference of dissolved CH$_4$ concentration (δCH$_4$) in surface waters between dusk and dawn as a function of bottom depth and CH$_4$ at dusk in Lake Victoria during three cruises (Table S7). Sampling was carried out during day-time and the ship anchored during the night. The difference between dusk and dawn provides an estimate of the maximum daily amplitude. The δCH$_4$ values ranged between -200 and 97 nmol L$^{-1}$, with a median of -6 nmol L$^{-1}$. A δCH$_4$ signal was measurable for bottom depths < 30 m. In 8 out 12 cases, δCH$_4$ was negative, possibly related to an enhanced removal of CH$_4$ by MOX due to the absence during night-time of light inhibition of microbial methane oxidation (MOX) (15). This explanation was also consistent with the general tendency of a stronger night-time decrease of CH$_4$ with increasing CH$_4$ levels at dusk, since MOX is a first order process, dependent upon substrate concentration (106). The positive δCH$_4$ signal might be indicative of input of CH$_4$ from bottom waters due to night-time convection. Solid grey line is a linear fit to the data (Table S3).
Maximal amplitude at stations repeatedly sampled during consecutive cruises (n) of dissolved CH$_4$ concentration, partial pressure of CO$_2$ (pCO$_2$) and N$_2$O saturation level (% N$_2$O) in surface waters, and chlorophyll-$a$ (Chl-$a$) concentration average for all cruises as a function of bottom depth in Lakes Victoria (n=3), Tanganyika (n=2), Kivu (n=4), Edward (n=4), and George (n=4). % N$_2$O showed extreme variability at 20 m in Lake Edward, due to strong mixing events induced by storms (not shown).
Fig. S16.

Vertical profiles of the partial pressure of CO\textsubscript{2} (pCO\textsubscript{2}), oxygen saturation level (%O\textsubscript{2}), and water temperature in Lakes Victoria (26/10/2018) and Edward (27/03/2017) during the periods of maximal observed stratification at stations with equivalent bottom depth (30 and 32 m, respectively). Horizontal dotted lines indicate equilibrium with the atmosphere. Note that in Lake Victoria bottom waters were still oxygenated unlike Lake Edward where they were anoxic. The maximum pCO\textsubscript{2} value measured in bottom waters of Lake Victoria was 6,507 ppm at 68 m depth in the deepest central part of the lake. We do not have a clear explanation for the higher pCO\textsubscript{2} values in bottom water of Lake Victoria compared to Lake Edward at similar depths. Vertical thermal stratification was weaker in Lake Edward than Lake Victoria, allowing more frequent vertical mixing (by storms for example) and lesser accumulation of CO\textsubscript{2} in bottom waters. Lower pCO\textsubscript{2} and higher %O\textsubscript{2} in surface waters indicated a higher primary production in surface waters of Lake Victoria than Edward, possibly sustaining a higher degradation of organic matter in bottom waters. In Lake Victoria, there could also be an important degradation in sediments of organic matter remnants of past periods with intense eutrophication (54,107).
Fig. S17.

Dissolved CH₄ concentration in surface waters versus lake surface area and lake average depth in lakes in Africa (this study), Amazon floodplains (108, 109), Pantanal (99), India (105,110), and Philippines (111).
Fig. S18.

Partial pressure of CO$_2$ (pCO$_2$) in surface waters versus lake mean depth in non-humic African lakes (this study), Lake Carioca in Brazil (112) and Lake Batur in Bali (113). Solid line and dotted lines represent the linear regression and the 95% confidence interval based on the African lakes only. The fact that the two non-African lakes fall within (or very close) to the 95% confidence interval is indicative that depth is a good predictor of CO$_2$ dynamics in non-humic tropical lakes, because depth drives levels of primary productivity (Fig. 2H), although, admittedly based only on two lakes. For consistency, only studies based on direct measurements of pCO$_2$ were selected, excluding data derived from the computation of pCO$_2$ from pH and total alkalinity, as this computation can provide erroneous and unrealistically high pCO$_2$ values (28).
Fig. S19.

Partial pressure of CO$_2$ (pCO$_2$) in surface waters versus lake surface area and dissolved organic carbon (DOC) concentration in humic African lakes (this study) and Amazon floodplain lakes (109,114,115). For consistency, only studies based on direct measurements of pCO$_2$ were selected, excluding data derived from the computation of pCO$_2$ from pH and total alkalinity, as this computation provides erroneous and unrealistically high pCO$_2$ values (28). We did not find reports of pCO$_2$ measured directly in humic tropical lakes other than in the Amazon basin. We only selected seasonally resolved studies, so we excluded an additional study reporting pCO$_2$ measured directly in Amazon floodplain lakes based on single cruise (116). The vertical dotted line indicates the threshold surface area (260 km$^2$) used separate the lakes in HydroLAKES to which different ΔpCO$_2$ values were used for the scaling of FCO$_2$. Note that at equivalent DOC values, pCO$_2$ in the Amazon lakes are higher than in African humic lakes. This might reflect the stronger hydrological connectivity of the Amazon floodplain lakes with the Amazon River, while the sampled African humic lakes were not floodplain lakes, hence more disconnected hydrological isolated from river networks.
Fig. S20.

Comparison of dissolved organic carbon (DOC) concentration measured in several African tropical lakes (“DOC(this study)”) versus modelled DOC (“DOC(Toming)”) (38) and difference of measured DOC and modelled DOC as function of measured chlorophyll-a (Chl-a) concentration. The model used as predictors of DOC a combination of precipitation and radiation data from WorldClim (63) and lake morphological attributes of HydroLAKES (29) and was trained with DOC observations (117) almost exclusively from boreal and temperate regions (only 1 tropical lake versus 7,513 boreal and temperate lakes). In African tropical lakes, the model fails to account for DOC inputs from wetlands in humic lakes and for phytoplankton exudation in productive non-humic lakes. Dotted line is the 1:1 line, solid lines are fitted to the data (Table S3).
Fig. S21.
Ship tracks during which continuous measurements of partial pressure of CO$_2$ (pCO$_2$) and dissolved CH$_4$ concentration were made in surface waters with an equilibrator (118) connected to a laser spectrometer in Lakes Victoria, Tanganyika, Albert and Edward (Table S7).
Fig. S22.
Comparison of partial pressure of CO₂ (pCO₂) and dissolved CH₄ concentration measured by two techniques in surface waters of Lakes Victoria, Tanganyika and Albert. On the X-axis, measurements of both pCO₂ and CH₄ with a LGR off-axis integrated cavity output spectroscopy analyzer coupled to an equilibrator (118) through which surface water was continuously pumped. On the Y-axis, measurements by headspace from samples collected in surface waters with a Niskin bottle, on-site with an infra-red gas analyzer (Li-cor Li-840) for pCO₂, and in the home laboratory by gas chromatography for CH₄. Insets show data on a linear scale, main panel shows data on a log-log scale. Solid black line shows 1:1 line, solid red line shows the linear regression.
Fig. S23.

Difference of lake surface water temperature in 76 tropical lakes (67) and air temperature from WorldClim (63) as a function of absolute latitude. Solid line is the fit to the data (Table S3).
Fig. S24.

Comparison of lake surface water temperature calculated from a relation with air temperature from WorldClim (63) (refer to Fig. S23) and average measured water temperature. Solid line is the fit to the data (Table S3).
Fig. S25.

Spatial variation of long-term average of wind speed over land from WorldClim (63).
Table S1: Morphological and catchment characteristics of the studied lakes, including the 24 sampled African lakes, plus Lake Malawi (48). Drainage area and catchment slope were derived from HydroSHEDS (65), catchment vegetation biomass from a pantropical national level carbon stock data-set (97), and catchment land cover from the Global Land Cover 2000 database of Africa (98). The relative coverage of flooded dense forest is indicative of the importance of wetland coverage on the catchment.

| Name          | Longitude °E | Latitude °N | Average depth m | Maximum depth m | Lake surface elevation m | Lake area km² | Drainage area km² | Catchment slope ° | Catchment vegetation biomass Mg km² | Catchment land cover Cropland veg./croplands % | Dense forest % | Flooded dense forest % | Forest open % | Mosaic Forest-Shrubland/Grassland % | Grasslands Flooded grasslands % | Shrublands Flooded grasslands % |
|---------------|-------------|-------------|-----------------|-----------------|--------------------------|---------------|------------------|-----------------|-----------------------------------|---------------------------------|----------------|-------------------------------|-------------|-------------------------------|---------------------------------|-------------------------------|
Table S2: Seasonally and spatially averaged water temperature (Wat. Temp.), partial pressure of CO$_2$ (pCO$_2$), air-water gradient of pCO$_2$ (ΔpCO$_2$), dissolved CH$_4$ concentration, dissolved N$_2$O concentration, N$_2$O saturation level (%N$_2$O) in surface waters, wind speed (sp.) from WorldClim (63), air-water flux of CO$_2$ (FCO$_2$), CH$_4$ (FCH$_4$, diffusive) and N$_2$O (FN$_2$O) in 24 African Lakes.

| Name          | Wat. temp. | pCO$_2$ | ΔpCO$_2$ | CH$_4$ | N$_2$O | %N$_2$O | Wind sp. | FCO$_2$ | FCH$_4$ | FN$_2$O |
|---------------|------------|---------|----------|--------|--------|---------|----------|--------|---------|---------|
|               | °C         | ppm     | ppm      | nmol L$^{-1}$ | nmol L$^{-1}$ | %       | m s$^{-1}$ | mmol m$^{-2}$ d$^{-1}$ | mmol m$^{-2}$ d$^{-1}$ | µmol m$^{-2}$ d$^{-1}$ |
| Victoria      | 25.6       | 274     | -118     | 54     | 7.8   | 112.6   | 2.3       | -3.2   | 0.04    | 0.70    |
| Tanganika     | 27.1       | 412     | 21       | 19     | 5.4   | 82.4    | 2.2       | 0.8    | 0.01    | -0.81   |
| Albert        | 28.5       | 435     | 45       | 73     | 8.2   | 130.0   | 2.0       | 1.1    | 0.06    | 1.5     |
| Kivu          | 23.5       | 907     | 536      | 62     | 7.3   | 105.0   | 2.0       | 13.8   | 0.04    | 0.27    |
| Edward        | 26.5       | 461     | 72       | 145    | 8.1   | 122.1   | 1.9       | 1.8    | 0.11    | 1.1     |
| Mai Ndombé    | 30.3       | 3143    | 2764     | 250    | 22.0  | 381.2   | 1.1       | 60.2   | 0.18    | 12.1    |
| Tumba         | 28.2       | 1752    | 1373     | 66     | 14.1  | 227.0   | 1.0       | 29.0   | 0.04    | 5.4     |
| George        | 25.8       | 30      | -363     | 124    | 5.4   | 78.6    | 2.1       | -9.4   | 0.09    | -1.1    |
| Kamuhoro      | 35.9       | 615     | 231      | 874    | 5.3   | 107.4   | 2.5       | 7.6    | 1.1     | 0.48    |
| Alaotra       | 23.6       | 1628    | 1232     | 33     | 6.5   | 88.3    | 2.1       | 32.1   | 0.02    | -0.64   |
| Ndala         | 22.0       | 6,491   | 4.8      | 63.0   | 1.8   | 4.3     | -2.0      |        |         |
| Nyamusingire  | 26.2       | 213     | -174     | 580    | 4.4   | 65.9    | 2.0       | -4.5   | 0.44    | -1.8    |
| Kyamwina      | 25.5       | 180     | -212     | 680    | 5.2   | 76.2    | 2.1       | -5.5   | 0.52    | -1.3    |
| Mbita         | 22.1       | 209     | 7.6      | 99.2   | 1.9   | 0.14    | -0.04     |        |         |
| Lukulu        | 22.8       | 1,808   | 5.2      | 69.2   | 1.8   | 1.2     | -1.6      |        |         |
| Yandja        | 34.9       | 960     | 4.7      | 97.1   | 1.1   | 0.81    | -0.13     |        |         |
| Mbalukira     | 21.0       | 309     | 17.9     | 224.0  | 1.9   | 0.20    | 6.7       |        |         |
| Nkugute       | 24.3       | 280     | -109     | 229    | 4.9   | 68.3    | 2.0       | -2.8   | 0.16    | -1.7    |
| Nyamunuka     | 25.8       | 112     | -276     | 490,749| 0.6   | 8.1     | 2.0       | -7.1   | 371.4   | -4.8    |
| Kitagata      | 28.6       | 693     | 303      | 13,858 | 0.6   | 10.0    | 2.0       | 7.8    | 11.2    | -4.6    |
| Mrambi        | 25.2       | 210     | -176     | 494    | 4.7   | 67.4    | 2.1       | -4.5   | 0.37    | -1.7    |
| Kyashanduka   | 24.5       | 11      | -384     | 118    | 4.3   | 60.9    | 2.0       | -9.9   | 0.08    | -2.1    |
| Katinda       | 24.9       | 83      | -306     | 136,508| 2.6   | 36.8    | 2.1       | -7.9   | 101.6   | -3.4    |
| Lac Vert      | 23.6       | 26,980  | 4.1      | 56.7   | 1.7   | 18.1    | -2.2      |        |         |
Table S3: Equations and statistics at 0.05 level of curve fits of data given in Figures.

| Figure | Function | Equation | r² | n  | p       | Comment                        |
|--------|----------|----------|----|----|---------|--------------------------------|
| 2      | log (CH₄) versus log (surface area) | y = -0.406x + 3.3742 | 0.40 | 24 | 0.0009  |                                |
| 2      | log (CH₄) versus log (mean depth) | y = -0.5245x + 3.2096 | 0.16 | 24 | 0.0561  |                                |
| 2      | pCO₂ versus log (surface area) | y = 38.258x + 222 | 0.14 | 15 | 0.1719  | excluding 4 humic lakes        |
| 2      | pCO₂ versus log (mean depth) | y = 110.21x + 167 | 0.27 | 15 | 0.0464  | excluding 4 humic lakes        |
| 2      | %NO₂ versus log (surface area) | y = 10.94x + 58.80 | 0.44 | 19 | 0.0021  | excluding 4 humic lakes        |
| 2      | %NO₂ versus log (mean depth) | y = 18.045x + 55.53 | 0.28 | 19 | 0.0204  | excluding 4 humic lakes        |
| 2      | log (CH₄-a) versus log (surface area) | y = -0.3292x + 1.7398 | 0.49 | 20 | 0.0004  | excluding 4 humic lakes        |
| 2      | log (CH₄-a) versus log (mean depth) | y = -0.7764x + 2.066 | 0.62 | 20 | <0.0001 | excluding 4 humic lakes        |
| 3      | log(pCO₂) versus log (primary production) | y = -1.0125x + 5.4839 | 0.81 | 15 | <0.0001 |                                |
| 3      | log(pCO₂) versus log (CH₄-a) | y = -0.5245x + 3.2096 | 0.16 | 24 | 0.0561  |                                |
| 3      | pCO₂ versus log (%O₂) | y = -82.76x + 17244 | 0.66 | 15 | 0.0002  | excluding 2 hypersaline lakes  |
| 3      | pCO₂ versus cyanobacteria abundance | y = 2980.6e⁻⁰.⁰³⁹x | 0.63 | 17 |        |                                |
| 3      | pCO₂ versus δ¹³C-DIC | y = 67.536x + 511.16 | 0.70 | 17 | <0.0001 |                                |
| 3      | pCO₂ versus DOC | y = 77.601x + 364 | 0.74 | 4  | 0.1395  |                                |
| 3      | pCO₂ versus DOC | y = -21.775x + 396 | 0.28 | 12 | 0.0767  |                                |
| 3      | log(pCO₂) versus log (CDOM SR) | y = -1.8939x + 2.7666 | 0.25 | 17 | 0.0359  |                                |
| 4      | CH₄ versus depth (L. Tanganyika <160 m) | y = -27.829ln(x) + 150 | 0.84 | 16 |        |                                |
| 4      | CH₄ versus depth (L. Edward) | y = -48.845ln(x) + 169 | 0.99 | 3  |        |                                |
| 4      | CH₄ versus depth (L. Albert) | y = -106.82ln(x) + 401 | 0.83 | 5  |        |                                |
| 4      | CH₄ versus depth (L. Victoria) | y = -110.35ln(x) + 451 | 0.96 | 8  |        |                                |
| 6      | log (CH₄) versus log (CH₄-a) | y = 0.6981x + 1.9221 | 0.28 | 23 | 0.0088  |                                |
| 6      | log (CH₄) versus log (CH₄-a) | y = -1.126x - 2.7975 | 0.58 | 23 | 0.0004  |                                |
| 8      | DOC versus log (CH₄-a) | y = 4.2116x + 0.8315 | 0.6  | 12 | 0.0028  | excluding 3 humic lakes        |
| S1     | %NO₂ versus %NO₃ | y = 1.4064x + 32.706 | 0.23 | 14 | 0.0827  |                                |
| S1     | %NO₂ versus %NO₄ | y = -1.4571x + 196.11 | 0.24 | 14 | 0.0765  |                                |
| S1     | log(%NO₂) versus log (primary production) | y = -0.3182x + 2.9195 | 0.57 | 14 | 0.0011  |                                |
| S1     | %NO₂ versus log (CH₄-a) | y = -5.885x + 169.88 | 0.35 | 23 | 0.0028  |                                |
| S1     | %NO₂ versus DOC | y = 6.1599x + 46.678 | 0.47 | 17 | 0.0025  |                                |
| S1     | %NO₂ versus CDOM SR | y = -94.39x + 250.61 | 0.32 | 16 | 0.0186  |                                |
| S7     | CO₂ versus HCO⁻₃ | y = 0.0016x + 1.166 | 0.65 | 12 | 0.0016  | excluding 4 humic and 2 hypersaline lakes |
| S11    | %CV versus CH₄-a | y = 2.7709x + 23.609 | 0.36 | 18 | 0.0084  |                                |
| S14    | CH₄ (dusk - dawn) versus CH₄ @ dusk | y = -0.2691x + 11.197 | 0.34 | 16 | 0.0182  |                                |
| S18    | pCO₂ versus log (mean depth) | y = 110.21x + 167 | 0.27 | 15 | 0.0464  | non-humic lakes only           |
| S20    | DOC (this study) versus DOC (Toming) | y = 2.6277x + 2.8232 | 0.15 | 16 | 0.1395  |                                |
| S20    | [DOC (this study) - DOC (Toming)] versus CH₄-a | y = 4.277x - 1.499 | 0.64 | 16 | 0.0019  |                                |
| S23    | (Air temp - water temp) versus absolute Latitude | y = 0.104x - 3.8563 | 0.39 | 72 | <0.0001 |                                |
| S24    | Calculated versus measured water temperature | y = 1.0513x - 1.4701 | 0.79 | 22 | <0.0001 | excluding Lakes Yandja and Kamohonjo |
Table S4: Air-water flux of CO₂ (FCO₂), CH₄ (FCH₄, diffusive) and N₂O (FΝ₂O) per m² and integrated for African tropical and pan-tropical lakes scaled from relations between air-water gradient of the partial pressure of CO₂ (ΔpCO₂), CH₄ and N₂O saturation level (%Ν₂O) as a function of depth and based on HydroLAKES data-base of lakes that were classified into humic and non-humic, plus area-averaged extrapolated pCO₂, CH₄, %Ν₂O, as well as, surface areas (SA), gas transfer velocity (k) compared to previous estimates (1,2,3,4,9,31,47). Cole et al (1) provided an average pCO₂ for African lakes but did not provide estimates regionalized for the tropics. Note that the “African lakes” reported by Cole et al. (1) correspond to 39 lakes located in Cameroon formed in volcanic basins (87), some of which strongly enriched in magmatic and volcanic CO₂ (119). The unrealistic surface area used by (47) combines natural lakes and reservoirs. Values with a single asterisk (*) correspond to a scaling using the original HydroLAKES (29) surface area, including an unrealistic surface area value of 18,752 km² for Lake Chad. Values with a double asterisk (**) were obtained with a more recent surface area value of 2603 km² for Lake Chad (30).

|                      | SA (km²) | k (cm h⁻¹) | pCO₂ (ppm) | FCO₂ (gC m⁻² yr⁻¹) | FCCH₄ (gCH₄ m⁻² yr⁻¹) | CH₄ (nmol L⁻¹) | diffusive FCH₄ (TgCH₄ yr⁻¹) | %Ν₂O | FΝ₂O (mgN₂O-N m⁻² yr⁻¹) | FΝ₂O (GgN₂O-N yr⁻¹) |
|----------------------|----------|-------------|-------------|---------------------|-----------------------|---------------|----------------------------|-------|-------------------------|---------------------|
| **African tropical lakes** (L. Chad SA = 18,752 km²) | | | | | | | | | | |
| Non-humic            | 187,481  | 2.9         | 394         | 0.4 ± 9.7           | 0.08 ± 1.9            | 321           | 1.6 ± 0.4                  | 0.3 ± 0.1 | 91                       | -2.7 ± 2.7          |
| Strongly humic       | 38,061   | 2.1         | 1,691       | 0.165 ± 42.5        | 6.3 ± 1.6             | 4683          | 26.9 ± 6.1                 | 1.0 ± 0.2 | 167                      | 19.9 ± 1.0          |
| Total                | 225,543  | 3.0         | 613         | 28.3 ± 8.4          | 6.4 ± 1.9             | 1057          | 5.8 ± 1.5                  | 1.3 ± 0.3 | 104                      | 11.7 ± 0.7          |
| (4)                  | 222,062  | 5.6         | 934         | 160.3               | 35.6                  |               |                           |         |                         |                     |
| (1)                  | 2.1      | 2.296       | 124.0       |                     |                       |               |                           |         |                         |                     |
| (21)                 | 229,000  |             |             |                     |                       |               |                           |         |                         | 16.1                | 3.7                 |
| **Pan-tropical lakes** (L. Chad SA = 18,752 km²) | | | | | | | | | | |
| Non-humic            | 246,925  | 2.9         | 367         | -2.9 ± 5.9          | -0.7 ± 1.4            | 334           | 1.6 ± 0.4                  | 0.4 ± 0.1 | 86                       | -4.0 ± 3.0          |
| Strongly humic       | 92,129   | 3.0         | 2,336       | 230.5 ± 59.9        | 21.2 ± 5.5            | 2255          | 12.7 ± 2.3                 | 1.2 ± 0.2 | 167                      | 18.9 ± 7.6          |
| Total                | 339,054  | 2.9         | 902         | 60.5 ± 31.5         | 20.5 ± 10.7           | 856           | 4.6 ± 1.2                  | 1.6 ± 0.4 | 108                      | 2.3 ± 4.1           |
| (9)                  | 585,536  | 2.1         | 1,804       | 176.0               | 103.1                 |               |                           |         |                         |                     |
| (47)                 | 1,840,000| 4.0         | 1,900       | 240.0               | 441.6                 |               |                           |         |                         |                     |
| (4)                  | 400,906  | 5.6         | 1,906       | 261.0               | 104.5                 |               |                           |         |                         |                     |
| (3)                  | 585,536  |             |             |                     |                       |               |                           |         |                         |                     |
| (31)                 | 345,870  |             |             |                     |                       |               |                           |         |                         | 18.7                | 6.47               |
Table S5: Ebullitive CH₄ fluxes (FCH₄) measured with inverted funnels (trapping surface area of 0.04 m²) and diffusive CH₄ fluxes derived from CH₄ concentration and gas transfer velocity (k) computed from wind speed.

| Name          | Date       | Trap deployment duration | Number of traps | Bottom depth | Water temperature | Wind speed | Chl-a CH₄ (surface water) | CH₄ (surface water) | Diffusive FCH₄ | Ebullitive FCH₄ |
|---------------|------------|--------------------------|-----------------|--------------|-------------------|------------|--------------------------|---------------------|----------------|----------------|
| Edward        | 21-03-2019 | 2.0                      | 2               | 10.2         | 27.0              | 0.5        | 33.0                     | 62                  | 36             | 198 ± 84       |
| George        | 25-03-2019 | 1.3                      | 4               | 2.5          | 29.2              | 0.5        | 57.4                     | 578                 | 363            | 8,547 ± 395    |
| Nyamusingire  | 28-03-2019 | 0.8                      | 6               | 3.0          | 25.7              | 0.5        | 59.9                     | 1575                | 909            | 21,324 ± 788   |
| Victoria      | 16-06-2019 | 0.5                      | 1               | 5.9          | 25.4              | 1.5        | 23.4                     | 220                 | 150            | 10             |
**Table S6**: Median and inter-quartile range of ebullitive CH$_4$ flux ($F$CH$_4$) upscaled to the littoral zone over two depth zones (0-4 and 4-10 m) derived from morphometric relations (74) and the mean depth from HydroLAKES (29), using the median of ebullitive $F$CH$_4$ measured in African lakes (Table S5) and compiled from literature (Fig. S10) in African tropical lakes and pan-tropical lakes, as well as previously published estimates (3). Values with a single asterisk (*) correspond to a scaling using the original HydroLAKES (29) surface area, including an unrealistic surface area value of 18,752 km$^2$ for Lake Chad. Values with a double asterisk (**) were obtained with a more recent surface area value of 2603 km$^2$ for Lake Chad (30).

|                         | Surface area km$^2$ | Median (IQR) Ebullitive $F$CH$_4$ TgCH$_4$ yr$^{-1}$ |
|-------------------------|---------------------|------------------------------------------------------|
| **African tropical lakes (*)** |                     |                                                      |
| This study (0-4 m)       | 52,133              | 1.7 (0.6-4.0)                                       |
| This study (4-10 m)      | 20,078              | 0.2 (0.1-0.8)                                       |
| **This study (0-10 m)**  | 72,211              | 1.9 (0.7-4.6)                                       |
| **Pan-tropical lakes (*)** |                     |                                                      |
| This study (0-4 m)       | 106,951             | 3.6 (1.2-7.9)                                       |
| This study (4-10 m)      | 44,403              | 0.5 (0.1-1.7)                                       |
| **This study (0-10 m)**  | 151,354             | 4.0 (1.4-9.7)                                       |
| **African tropical lakes (**)** |                     |                                                      |
| This study (0-4 m)       | 35,985              | 1.2 (0.4-2.7)                                       |
| This study (4-10 m)      | 20,078              | 0.2 (0.1-0.8)                                       |
| **This study (0-10 m)**  | 56,063              | 1.4 (0.5-3.5)                                       |
| **Pan-tropical lakes (**)** |                     |                                                      |
| This study (0-4 m)       | 90,803              | 3.0 (1.1-6.7)                                       |
| This study (4-10 m)      | 44,403              | 0.5 (0.1-1.7)                                       |
| **This study (0-10 m)**  | 135,206             | 3.5 (1.2-8.5)                                       |
| Previous studies         | 585,536             | 22.2 ± 12.7                                         |
Table S7: Sampling dates and number of samples (n) collected in surface waters for partial pressure of CO$_2$ (pCO$_2$), CH$_4$ and N$_2$O concentrations in surface waters in 24 tropical African lakes. Italicized numbers in brackets correspond to continuous measurements in surface waters with an equilibrator and a laser analyzer, other numbers to discrete samples analyzed by headspace technique. All data are unpublished except for the 2007-2009 cruises in Lake Kivu (49,55).

| Name         | Sampling dates       | pCO$_2$ n= | CH$_4$ n= | N$_2$O n= |
|--------------|----------------------|------------|-----------|-----------|
| Victoria     | 29/03-08/04/2018     | 26 (7379)  | 26 (7379) | 26        |
|              | 25/10-04/11/2018     | 23 (5976)  | 23 (5976) | 23        |
|              | 07/06-17/06/2019     | 30 (6579)  | 30 (6579) | 30        |
| Tanganyika   | 08/10-18/10/2019     | 30 (7334)  | 30 (7334) | 30        |
|              | 01/05-07/05/2021     | 22         | 22        | 22        |
| Albert       | 20/06-23/06/2019     | 12 (1364)  | 12 (1364) | 12        |
| Kivu         | 15/03-29/03/2007     | 14         | 14        | nd        |
|              | 28/08-10/09/2007     | 14         | 14        | nd        |
|              | 21/06-03/07/2008     | 14         | 14        | nd        |
|              | 21/04-05/05/2009     | 14         | 14        | nd        |
|              | 19/10-27/10/2010     | 9          | 9         | 9         |
| Edward       | 20/10-04/11/2016     | 14         | 14        | 14        |
|              | 23/03-31/03/2017     | 14         | 14        | 14        |
|              | 18/01-02/02/2018     | 14         | 14        | 14        |
|              | 21/03-30/03/2019     | 4 (504)    | 4 (504)   | 4 (504)   |
| Mai Ndombe   | 03/05-03/05/2015     | 1          | 1         | 1         |
| Tumba        | 24/06-24/06/2014     | 1          | 1         | 1         |
| George       | 24/10-24/10/2016     | 1          | 1         | 1         |
|              | 01/04-01/04/2017     | 3          | 3         | 3         |
|              | 28/01-28/01/2018     | 2          | 2         | 2         |
|              | 25/03-25/03/2019     | 1          | 1         | 1         |
| Kamohonjo    | 01/10-02/10/2019     | 9          | 9         | 9         |
| Alaotra      | 23/05-23/05/2019     | 4          | 4         | 4         |
|              | 19/01-01/02/2019     | 6          | 6         | 6         |
|              | 26/08-01/09/2019     | 5          | 5         | 5         |
| Ndalaga      | 30/06-30/06/2011     | nd         | 1         | 1         |
|              | 01/02-01/02/2012     | nd         | 1         | 1         |
| Nyamusingere | 02/11-02/11/2016     | 5          | 5         | 5         |
|              | 04/04-04/04/2017     | 1          | 1         | 1         |
|              | 25/01-25/01/2018     | 1          | 1         | 1         |
|              | 28/03-28/03/2019     | 2          | 2         | 2         |
| Kyamwinga    | 06/04-06/04/2017     | 1          | 1         | 1         |
| Mbita        | 02/07-02/07/2011     | nd         | 1         | 1         |
|              | 02/02-02/02/2012     | nd         | 1         | 1         |
| Lukulu       | 01/02-01/02/2012     | nd         | 1         | 1         |
| Yandja       | 06/05-06/05/2010     | nd         | 1         | 1         |
| Mbalukira    | 01/07-01/07/2011     | nd         | 1         | 1         |
|              | 31/01-31/01/2012     | nd         | 1         | 1         |
| Nkugute      | 01/11-01/11/2016     | 1          | 1         | 1         |
|              | 03/04-03/04/2107     | 1          | 1         | 1         |
|              | 30/01-30/01/2018     | 1          | 1         | 1         |
| Nyamuruka    | 02/11-02/11/2016     | 1          | 1         | 1         |
| Kitagata     | 08/04-08/04/2017     | 1          | 1         | 1         |
| Mrambi       | 07/04-07/04/2017     | 1          | 1         | 1         |
| Kyashanduka  | 25/01-25/02/2018     | 1          | 1         | 1         |
| Kaltinda     | 06/11-07/11/2016     | 3          | 3         | 3         |
|              | 05/04-05/04/2017     | 1          | 1         | 1         |
|              | 31/01-31/01/2018     | 1          | 1         | 1         |
| Lac Vert     | 28/06-28/06/2011     | nd         | 1         | 1         |
|              | 29/01-29/01/2012     | nd         | 1         | 1         |
Table S8: Alternative upscaling of air-water gradient of the partial pressure of CO$_2$ ($\Delta$pCO$_2$) and corresponding air-water CO$_2$ flux (FCO$_2$) in African lakes using surface areas from Hydrolakes (29) but with the more recent and realistic surface area of Lake Chad (30). N°1: surface area weighted average for available 25 lakes of $\Delta$pCO$_2$ = 12 ppm for both humic and non-humic lakes; N°2: $\Delta$pCO$_2$ = 71.126 x DOC - 367 ($r^2$=0.53, $p$= 0.0012, $n$=16), where DOC is dissolved organic carbon concentration for both humic and non-humic lakes, and applied to modelled DOC (35) for HydroLAKES (25), N°3: for non-humic lakes $\Delta$pCO$_2$ = 50.509 x log(lake surface area) - 165 ($r^2$=0.17, $p$= 0.1263, $n$=15); for humic lakes $\Delta$pCO$_2$ = 0.9578 x lake surface area + 583 ($r^2$=0.86, $p$= 0.0731, $n$=4).

|                | Surface area | FCO$_2$ | FCO$_2$ |
|----------------|--------------|---------|---------|
|                | km$^2$       | gC m$^{-2}$ yr$^{-1}$ | TgC yr$^{-1}$ |
| **Alternative up-scaling N°1** |              |         |         |
| Non-humic African lakes | 187,481 | 1.4 | 0.3 |
| Strongly humic African lakes | 21,913 | 1.4 | 0.03 |
| Total African lakes | 209,394 | 1.4 | 0.3 |
| **Alternative up-scaling N°2** |              |         |         |
| Non-humic African lakes | 187,481 | -22.5 | -4.2 |
| Strongly humic African lakes | 21,913 | -6.8 | -0.1 |
| Total African lakes | 209,394 | -20.9 | -4.4 |
| **Alternative up-scaling N°3** |              |         |         |
| Non-humic African lakes | 187,481 | 5.4 | 1.02 |
| Strongly humic African lakes | 21,913 | 214.7 | 4.7 |
| Total African lakes | 209,394 | 27.3 | 5.7 |
REFERENCES AND NOTES

1. J. J. Cole, N. F. Caraco, G. W. Kling, T. K. Kratz, Carbon dioxide supersaturation in the surface waters of lakes. Science 265, 1568–1570 (1994).

2. S. Sobek, L. J. Tranvik, J. J. Cole, Temperature independence of carbon dioxide supersaturation in global lakes. Global Biogeochem. Cycles 19, GB2003 (2005).

3. D. Bastviken, L. J. Tranvik, J. A. Downing, P. M. Crill, A. Enrich-Prast, Freshwater methane emissions offset the continental carbon sink. Science 331, 50–50 (2011).

4. P. A. Raymond, J. Hartmann, R. Lauerwald, S. Sobek, C. McDonald, M. Hoover, D. Butman, R. Striegl, E. Mayorga, C. Humborg, P. Kortelainen, H. Dürr, M. Meybeck, P. Ciais, P. Guth, Global carbon dioxide emissions from inland waters. Nature 503, 355–359 (2013).

5. T. DelSontro, J. J. Beaulieu, J. A. Downing, Greenhouse gas emissions from lakes and impoundments: Upscaling in the face of global change. Limnol. Oceanogr. Lett. 3, 64–75 (2018).

6. W. M. Lewis Jr. Tropical limnology. Annu. Rev. Ecol. Syst. 18, 159–184 (1987).

7. J. Langeveld, A. F. Bouwman, W. J. van Hoek, L. Vilmin, A. H. W. Beusen, J. M. Mogollón, J. J. Middelburg, Estimating dissolved carbon concentrations in global soils: A global database and model. SN Appl. Sci. 2, 1626 (2020).

8. J. F. Lapierre, P. A. del Giorgio, Geographical and environmental drivers of regional differences in the lake pCO$_2$ versus DOC relationship across northern landscapes, J. Geophys. Res. 117, G03015 (2012).

9. H. Marotta, C. M. Duarte, S. Sobek, A. Enrich-Prast, Large CO$_2$ disequilibria in tropical lakes. Global Biogeochem. Cycles 23, GB4022 (2009).

10. S. Kosten, F. Roland, D. M. L. Da Motta Marques, E. H. Van Nes, N. Mazzeo, L. da S. L. Sternberg, M. Scheffer, J. J. Cole, Climate-dependent CO$_2$ emissions from lakes. Global Biogeochem. Cycles 24, GB2007 (2010).
11. J. R. Helms A. Stubbins, J. D. Ritchie, E. C. Minor, D. J. Kieber, K. Mopper, Absorption spectral slopes and slope ratios as indicators of molecular weight, source, and photobleaching of chromophoric dissolved organic matter. *Limnol. Oceanogr.* **53**, 955–969 (2008).

12. P. A. del Giorgio, R. H. Peters, Patterns in planktonic $P:R$ ratios in lakes: Influence of lake trophy and dissolved organic carbon. *Limnol. Oceanogr.* **39**, 772–787 (1994).

13. S. Sobek, G. Algesten, A.-K. Bergström, M. Jansson, L. Tranvik, The catchment and climate regulation of pCO$_2$ in boreal lakes. *Glob. Change Biol.* **9**, 630–641 (2003).

14. J. P. Casas-Ruiz, J. Jakobsson, P. A. del Giorgio, The role of lake morphometry in modulating surface water carbon concentrations in boreal lakes. *Environ. Res. Lett.* **16**, 074037 (2021).

15. K. Sand-Jensen, P. A. Staehr, Scaling of pelagic metabolism to size, trophy and forest cover in small Danish lakes. *Ecosystems* **10**, 128–142 (2007).

16. R. Wanninkhof, Relationship between wind speed and gas exchange over the ocean. *J. Geophys. Res.* **97**, 7373–7382 (1992).

17. A. V. Borges, F. Darchambeau, T. Lambert, C. Morana, G. H. Allen, E. Tambwe, A. Toengaho Sembaito, T. Mambo, J. Nlandu Wabakhangazi, J.-P. Descy, C. R. Teodoru, S. Bouillon, Variations in dissolved greenhouse gases (CO$_2$, CH$_4$, N$_2$O) in the Congo River network overwhelmingly driven by fluvial-wetland connectivity. *Biogeosciences* **16**, 3801–3834 (2019).

18. C. S. Reynolds, *The Ecology of Phytoplankton* (Cambridge Univ. Press, 2006).

19. M. J. Bogard, P. A. del Giorgio, L. Boutet, M. C. G. Chaves, Y. T. Prairie, A. Merante, A. M. Derry, Oxic water column methanogenesis as a major component of aquatic CH$_4$ fluxes. *Nat. Commun.*, **5**, 5350 (2014).

20. M. Bižić, T. Klintzsch, D. Ionescu, M. Y. Hindiyeh, M. Günthel, A. M. Muro-Pastor, W. Eckert, T. Urich, F. Keppler, H.-P. Grossart, Aquatic and terrestrial cyanobacteria produce methane. *Sci. Adv.* **6**, eaax5343 (2020).
21. H.-P. Grossart, K. Frindt, C. Dziallas, W. Eckert, K. W. Tang, Microbial methane production in oxygenated water column of an oligotrophic lake. *Proc. Natl. Acad. Sci. U.S.A.* **108**, 19657–19661 (2011).

22. C. Morana, S. Bouillon, V. Nolla-Ardèvol, F. A. E. Roland, W. Okello, J.-P. Descy, A. Nankabirwa, E. Nabafu, D. Springael, A. V. Borges, Methane paradox in tropical lakes? Sedimentary fluxes rather than pelagic production in oxic conditions sustain methanotrophy and emissions to the atmosphere. *Biogeosciences* **17**, 5209–5221 (2020).

23. R. I. Jones, The influence of humic substances on lacustrine planktonic food chains. *Hydrobiologia* **229**, 73–91 (1992).

24. G. Yvon-Durocher, A. P. Allen, D. Bastviken, R. Conrad, C. Gudasz, A. St-Pierre, N. Thanh-Duc, P. A. del Giorgio, Methane fluxes show consistent temperature dependence across microbial to ecosystem scales. *Nature* **507**, 488–491 (2014).

25. P. Kankaala, J. Huotari, T. Tulonen, A. Ojala, Lake-size dependent physical forcing drives carbon dioxide and methane effluxes from lakes in a boreal landscape, *Limnol. Oceanogr.* **58**, 1915–1930 (2013).

26. M. A. Holgerson, P. A. Raymond, Large contribution to inland water CO₂ and CH₄ emissions from very small ponds, *Nat. Geosci.* **9**, 222–226 (2016).

27. S. R. Alin, T. C. Johnson, Carbon cycling in large lakes of the world: A synthesis of production, burial, and lake-atmosphere exchange estimates, *Global Biogeochem. Cycles* **21**, GB3002 (2007).

28. G. Abril, S. Bouillon, F. Darchambeau, C. R. Teodoru, T. R. Marwick, F. Tamooh, F. O. Omengo, N. Geeraert, L. Deirmendjian, P. Polsenaere, A. V. Borges, Technical note: Large overestimation of pCO₂ calculated from pH and alkalinity in acidic, organic-rich freshwaters. *Biogeosciences* **12**, 67–78 (2015).

29. M. L. Messager, B. Lehner, G. Grill, I. Nedeva, O. Schmitt, Estimating the volume and age of water stored in global lakes using a geo-statistical approach. *Nat. Commun.* **7**, 13603 (2016).
30. B. Pham-Duc, F. Sylvestre, F. Papa, F. Frappart, C. Bouchez, J.-F. Crétaux, The Lake Chad hydrology under current climate change. *Sci. Rep.* **10**, 5498 (2020).

31. R. Lauerwald, P. Regnier, V. Figueiredo, A. Enrich-Prast, D. Bastviken, B. Lehner, T. Maavara, P. Raymond, Natural lakes are a minor global source of N₂O to the atmosphere. *Global Biogeochem. Cycles*, **33**, 1564–1581 (2019).

32. J. M. Melack, L. L. Hess, M. Gastil, B. R. Forsberg, S. K. Hamilton, I. B. T. Lima, E. M. L. M. Novo, Regionalization of methane emissions in the Amazon Basin with microwave remote sensing. *Glob. Change Biol.* **10**, 530–544 (2004).

33. M. Saunois, P. Bousquet, B. Poulter, A. Peregon, P. Ciais, J. G. Canadell, E. J. Dlugokencky, G. Etiopie, D. Bastviken, S. Houweling, G. Janssens-Maenhout, F. N. Tubiello, S. Castaldi, R. B. Jackson, M. Alexe, V. K. Arora, D. J. Beerling, P. Bergamaschi, D. R. Blake, G. Brailsford, V. Brovkin, L. Bruhwiler, C. Crevoisier, P. Crill, K. Covey, C. Curry, C. Frankenber, N. Gedney, L. Höglund-Isaksson, M. Ishizawa, A. Ito, F. Joos, H.-S. Kim, T. Kleinen, P. Krummel, J.-F. Lamarque, R. Langenfelds, R. Locatelli, T. Machida, S. Maksyutov, Kyle C. Mc Donald, J. Marshall, J. R. Melton, I. Morino, V. Naik, S. O'Doherty, F.-J. W. Parmentier, P. K. Patra, C. Peng, S. Peng, G. P. Peters, I. Pison, C. Prigent, R. Prinn, M. Ramonet, W. J. Riley, M. Saito, M. Santini, R. Schroeder, I. J. Simpson, R. Spahni, P. Steele, A. Takizawa, B. F. Thornton, H. Tian, Y. Tohjima, N. Violy, A. Voulgarakis, M. van Weele, Guido R. van der Werf, R. Weiss, C. Wiedinmyer, D. J. Wilton, A. Wiltshire, D. Worthy, D. Wunch, X. Xu, Y. Yoshida, B. Zhang, Z. Zhang, Q. Zhu, The global methane budget. *Earth Syst. Sci. Data* **8**, 697–751 (2016).

34. A. V. Borges, F. Darchambeau, C. R. Teodoro, T. R. Marwick, F. Tamooh, N. Geeraert, F. O. Omengo, F. Guérin, T. Lambert, C. Morana, E. Okuku, S. Bouillon, Globally significant greenhouse gas emissions from African inland waters. *Nat. Geosci.* **8**, 637–642 (2015).

35. A. V. Borges, G. Abril, F. Darchambeau, C. R. Teodoro, J. Deborde, L. O. Vidal, T. Lambert, S. Bouillon, Divergent biophysical controls of aquatic CO₂ and CH₄ in the World's two largest rivers. *Sci. Rep.* **5**, 15614 (2015).
36. J. F. Talling, The annual cycle of stratification and phytoplankton growth in Lake Victoria (East Africa). *Int. Rev. gesamten Hydrobiol., Syst. Beih.* **51**, 545–621 (1966).

37. L. Pinho, C. M. Duarte, H. Marotta, A. Enrich-Prast, Temperature dependence of the relationship between pCO$_2$ and dissolved organic carbon in lakes. *Biogeosciences* **13**, 865–871 (2016).

38. K. Toming, J. Kotta, E. Uuemaa, S. Sobek, T. Kutser, L. J. Tranvik, Predicting lake dissolved organic carbon at a global scale. *Sci. Rep.* **10**, 8471 (2020).

39. C. Verpoorter, T. Kutser, D. A. Seekell, L. J. Tranvik, A global inventory of lakes based on high-resolution satellite imagery. *Geophys. Res. Lett.* **41**, 6396–6402 (2014).

40. T. W. Drake, P. A. Raymond, R. G. M. Spencer, Terrestrial carbon inputs to inland waters: A current synthesis of estimates and uncertainty. *Limnol. Oceanogr. Lett.* **3**, 132–142 (2018).

41. J. J. Cole, Y. T. Prairie, N. F. Caraco, W. H. McDowell, L. J. Tranvik, R. G. Striegl, C. M. Duarte, P. Kortelainen, J. A. Downing, J. J. Middelburg, J. Melack, Plumbing the global carbon cycle: Integrating inland waters into the terrestrial carbon budget. *Ecosystems* **10**, 172–185 (2007).

42. R. Kindler, J. Siemens, K. Kaiser, D. C. Walmsley, C. Bernhofer, N. Buchmann, P. Cellier, W. Eugster, G. Gleixner, T. Grunwald, A. Heim, A. Ibrom, S. K. Jones, M. Jones, K. Klumpp, W. Kutsch, L. K. Steenberg, S. Lehuger, B. Loubet, R. McKenzie, E. Moors, B. Osborne, K. Pilegaard, C. Rebmann, M. Saunders, M. W. I. Schmidt, M. Schrumpf, J. Seyfferth, U. Skiba, J.-F. Soussana, M. A. Sutton, C. Tefs, B. Vowinckel, M. J. Zeeman, M. Kaupenjohann, Dissolved carbon leaching from soil is a crucial component of net ecosystem carbon balance. *Glob. Change Biol.* **17**, 1167–1185 (2011).

43. W. Liang, W. Zhang, Z. Jin, J. Yan, Y. Lü, S. Wang, B. Fu, S. Li, Q. Ji, F. Gou, S. Fu, S. An, F. Wang, Estimation of global grassland net ecosystem carbon exchange using a model tree ensemble approach. *J. Geophys. Res. Biogeosci.* **125**, e2019JG005034 (2020).

44. J. Zeng, T. Matsunaga, Z.-H. Tan, N. Saigusa, T. Shirai, Y. Tang, S. Peng, Y. Fukuda, Global terrestrial carbon fluxes of 1999–2019 estimated by upscaling eddy covariance data with a random forest. *Sci. Data* **7**, 313 (2020).
45. W. Ludwig, J. L. Probst, S. Kempe, Predicting the oceanic input of organic carbon by continental erosion, *Global Biogeochem. Cycles* **10**, 23–41 (1996).

46. G. Abril, A. V. Borges, Ideas and perspectives: Carbon leaks from flooded land: Do we need to replumb the inland water active pipe? *Biogeosciences* **16**, 769–784 (2019).

47. A. K. Aufdenkampe, E. Mayorga, P. A. Raymond, J. M. Melack, S. C. Doney, S. R. Alin, R. E. Aalto, K. Yoo, Riverine coupling of biogeochemical cycles between land, oceans, and atmosphere. *Front. Ecol. Environ.* **9**, 53–60 (2011).

48. M. J. Ngochera, H. A. Bootsma, Spatial and temporal dynamics of pCO$_2$ and CO$_2$ flux in tropical Lake Malawi. *Limnol. Oceanogr.* **65**, 1594–1607 (2020).

49. A. V. Borges, G. Abril, B. Delille, J.-P. Descy, F. Darchambeau, Diffusive methane emissions to the atmosphere from Lake Kivu (Eastern Africa), *J. Geophys. Res.* **116**, G03032 (2011).

50. P. Kortelainen, T. Larmola, M. Rantakari, S. Juutinen, J. Alm, P. J. Martikainen, Lakes as nitrous oxide sources in the boreal landscape. *Glob. Change Biol.* **26**, 1432–1445 (2020).

51. E. O. Okuku, S. Bouillon, M. Tole, A. V. Borges, Diffusive emissions of methane and nitrous oxide from a cascade of tropical hydropower reservoirs in Kenya, *Lakes Reserv.* **24**, 127–135 (2019).

52. C. R. Teodoru, F. C. Nyoni, A. V. Borges, F. Darchambeau, I. Nyambe, S. Bouillon, Spatial variability and temporal dynamics of greenhouse gas (CO$_2$, CH$_4$, N$_2$O) concentrations and fluxes along the Zambezi River mainstem and major tributaries. *Biogeosciences* **12**, 2431–2453 (2015).

53. G. Abril, F. Guérin, S. Richard, R. Delmas, C. Galy-Lacaux, P. Gosse, A. Tremblay, L. Varfalvy, M. Aurelio Dos Santos, B. Matvienko, Carbon dioxide and methane emissions and the carbon budget of a 10-year old tropical reservoir (Petit Saut, French Guiana). *Global Biogeochem. Cycles* **19**, GB4007 (2005).

54. L. Deirmendjian, J.-P. Descy, C. Morana, W. Okello, M. P. Stoyneva-Gärtner, S. Bouillon, A. V. Borges, Limnological changes in Lake Victoria since the mid-20$^{\text{th}}$ century, *Freshw. Biol.* **66**, 1630–1647 (2021).
55. A. V. Borges, C. Morana, S. Bouillon, P. Servais, J.-P. Descy, F. Darchambeau, Carbon cycling of Lake Kivu (East Africa): Net autotrophy in the epilimnion and emission of CO$_2$ to the atmosphere sustained by geogenic inputs. *PLOS ONE* **9**, e109500 (2014).

56. S. Yamamoto, J. B. Alcauskas, T. E. Crozier, Solubility of methane in distilled water and seawater. *J. Chem. Eng. Data* **21**, 78–80 (1976).

57. R. F. Weiss, B. A. Price, Nitrous oxide solubility in water and seawater. *Mar. Chem.* **8**, 347–359 (1980).

58. C. W. Hunt, L. Snyder, J. E. Salisbury, D. Vandemark, W. H. McDowell, SIPCO2: A simple, inexpensive surface water pCO$_2$ sensor. *Limnol. Oceanogr. Methods* **15**, 291–301 (2017).

59. M. D. Mackey, D. J. Mackey, H. W. Higgins, S. W. Wright, CHEMTAX—A program for estimating class abundances from chemical markers: Application to HPLC measurements of phytoplankton. *Mar. Ecol. Progr. Ser.* **144**, 265–283. (1996).

60. APHA, *Standard Methods For The Examination Of Water And Wastewater* (American Public Health Association, 1998).

61. Standing Committee Of Analysts, *Ammonia in Waters: Methods for the Examination of Waters and Associated Materials* (H.M.S.O., 1981), 16 pp.

62. E. Fluet-Chouinard, B. Lehner, L.-M. Rebelo, F. Papa, S. K. Hamilton, Development of a global inundation map at high spatial resolution from topographic downscaling of coarse-scale remote sensing data. *Remote Sens Environ.* **158**, 348–361 (2015).

63. S. E. Fick, R. J. Hijmans, WorldClim 2: New 1km spatial resolution climate surfaces for global land areas. *Int. J. Climatol.* **37**, 4302–4315 (2017).

64. J. J. Cole, N. F. Caraco, Atmospheric exchange of carbon dioxide in a low-wind oligotrophic lake measured by the addition of SF$_6$. *Limnol. Oceanogr.* **43**, 647–656 (1998).
65. B. Lehner, K. Verdin, A. Jarvis, New global hydrography derived from spaceborne elevation data. *Eos, 89*, 93–94 (2008).

66. J.-F. Lapierre, D. A. Seekell, C. T. Filstrup, S. M. Collins, C. Emi Fergus, P. A. Soranno, K. S. Cheruvelil, Continental-scale variation in controls of summer CO2 in United States lakes. *J. Geophys. Res. Biogeosci.* **122**, 875–885 (2017).

67. S. C. Maberly R. A. O'Donnell, R. I. Woolway, M. E. J. Cutler, M. Gong, I. D. Jones, C. J. Merchant, C. A. Miller, E. Politi, E. M. Scott, S. J. Thackeray, A. N. Tyler, Global lake thermal regions shift under climate change, *Nat. Commun.* **11** :1232 (2020).

68. J. Verbeke, Recherches écologiques sur la faune des grands lacs de l’est du Congo belge. Bulletin de l'Institut royal des Sciences naturelles de Belgique : Résultats scientifiques de l'exploration hydrobiologique (1952-1954) des lacs Kivu, Edouard et Albert (1957).

69. S. E. Hamilton, “Creation of a bathymetric map of Lake Victoria, Africa” (2016); http://dx.doi.org/10.7910/DVN/SOEKNR.

70. S. MacIntyre, A. T. Crowe, A. Cortés, L. Arneborg, Turbulence in a small arctic pond. *Limnol. Oceanogr.* **63**, 2337–2358 (2018).

71. D. Vachon, Y. T. Prairie, The ecosystem size and shape dependence of gas transfer velocity versus wind speed relationships in lakes. *Can. J. Fish. Aquat. Sci.* **70**, 1757–1764 (2013).

72. T. DelSontro, L. Boutet, A. St-Pierre, P. A. del Giorgio, Y. T. Prairie, Methane ebullition and diffusion from northern ponds and lakes regulated by the interaction between temperature and system productivity, *Limnol. Oceanogr.* **61**, S62–S77 (2016)

73. M. Wik, P. M. Crill, R. K. Varner, D. Bastviken, Multiyear measurements of ebullitive methane flux from three subarctic lakes. *J. Geophys. Res. Biogeosci.* **118**, 1307–1321 (2013).

74. J. Håkan, A. A. Brolin, L. Håkanson, New approaches to the modelling of lake basin morphometry, *Environ. Model. Assess.* **12**, 213–228 (2007).
75. R. G. Wetzel, *Limnology: Lake & River Ecosystems* (Academic Press, ed. 3, 2001), p. 429.

76. P. A. del Giorgio, J. J. Cole, N. F. Caraco, R. H. Peters, Linking planktonic biomass and metabolism to net gas fluxes in northern temperate lakes. *Ecology* **80**, 1422–1431 (1999).

77. K. Finlay, P. R. Leavitt, A. Patoine, B. Wissel, Magnitudes and controls of organic and inorganic carbon flux through a chain of hardwater lakes on the northern Great Plains, *Limnol. Oceanogr.* **55**, 1551–1564 (2010).

78. H. Marotta, C. M. Duarte, L. Pinho, A. Enrich-Prast, Rainfall leads to increased pCO$_2$ in Brazilian coastal lakes, *Biogeosciences* **7**, 1607–1614 (2010).

79. M. A. Xenopoulos, D. M. Lodge, J. Frentress, T. A. Kreps, S. D. Bridgham, E. Grossman, C. J. Jackson, Regional comparisons of watershed determinants of dissolved organic carbon in temperate lakes from the Upper Great Lakes region and selected regions globally, *Limnol. Oceanogr.* **48**, 2321–2334 (2003).

80. J. A. Zwart, Z. J. Hanson, J. Vanderwall, D. Bolster, A. Hamlet, S. E. Jones, Spatially explicit, regional-scale simulation of lake carbon fluxes, *Global Biogeochem. Cycles* **32**, 1276–1293 (2018).

81. P. A. Staehr, L. Baastrup-Spohr, K. Sand-Jensen, C. Stedmon, Lake metabolism scales with lake morphometry and catchment conditions, *Aquat. Sci.* **74**, 155–169 (2012).

82. J. P. Casas-Ruiz, R. H. S. Hutchins, P. A. del Giorgio, Total aquatic carbon emissions across the boreal biome of Québec driven by watershed slope. *J. Geophys. Res. Biogeosci.* **126**, e2020JG005863 (2021).

83. G. W. Kling, Comparative transparency, depth of mixing, and stability of stratification in lakes of Cameroon, West Africa, *Limnol. Oceanogr.* **33**, 27–40 (1988).

84. E. G. Stets, D. Butman, C. P. McDonald, S. M. Stackpoole, M. D. DeGrandpre, R. G. Striegl, Carbonate buffering and metabolic controls on carbon dioxide in rivers, *Global Biogeochem. Cycles* **31**, 663–677 (2017).
85. J. Schenk, H. O. Sawakuchi, A. K. Sieczko, G. Pajala, D. Rudberg, E. Hagberg, K. Fors, H. Laudon, J. Karlsson, D. Bastviken, Methane in lakes: Variability in stable carbon isotopic composition and the potential importance of groundwater input *Front. Earth Sci.* **9**, 722215 (2021).

86. W. E. West, K. P. Creamer, S. E. Jones, Productivity and depth regulate lake contributions to atmospheric methane, *Limnol. Oceanogr.* **61**, S51-S61 (2016).

87. Bastviken, D., J. Cole, M. Pace, L. Tranvik, Methane emissions from lakes: Dependence of lake characteristics, two regional assessments, and a global estimate. *Global Biogeochem. Cycles* **18**, GB4009 (2004).

88. F. A. E. Roland, F. Darchambeau, C. Morana, A. V. Borges, Nitrous oxide and methane seasonal variability in the epilimnion of a large tropical meromictic lake (Lake Kivu, East-Africa), *Aquat. Sci.* **79**, 209–218 (2017).

89. K. Desrosiers, T. DelSontro, P. A. del Giorgio, Disproportionate contribution of vegetated habitats to the CH$_4$ and CO$_2$ budgets of a boreal lake. *Ecosystems* (2021).

90. E. S. Oliveira Junior, T. J. H. M. van Bergen, J. Nauta, A. Budiša, R. C. H. Aben, S. T. J. Weideveld, C. A. de Souza, C. C. Muniz, J. Roelofs, L. P. M. Lamers, S. Kosten, Water hyacinth’s effect on greenhouse gas fluxes: A field study in a wide variety of tropical water bodies, *Ecosystems* **24**, 988–1004 (2021).

91. J. E. Fernández, F. Peeters, H. Hofmann, On the methane paradox: Transport from shallow water zones rather than in situ methanogenesis is the major source of CH$_4$ in the open surface water of lakes. *J. Geophys. Res. Biogeosci.* **121**, 2717–2726 (2016).

92. T. DelSontro, P. A. del Giorgio, Y. T. Prairie, No longer a paradox: The interaction between physical transport and biological processes explains the spatial distribution of surface water methane within and across lakes, *Ecosystems*, **21**, 1073–1087 (2018).

93. H. Wang, L. Yang, W. Wang, J. Lu, C. Yin, Nitrous oxide (N$_2$O) fluxes and their relationships with water-sediment characteristics in a hyper-eutrophic shallow lake, China. *J. Geophys. Res.* **112**, G01005 (2007).
94. C. Soued, P. A. del Giorgio, R. Maranger, Nitrous oxide sinks and emissions in boreal aquatic networks in Quebec. *Nat. Geosci.* **9**, 116–120 (2015).

95. M. Mengis, R. Gächter, B. Wehrli, Sources and sinks of nitrous oxide (N$_2$O) in deep lakes. *Biogeochemistry* **38**, 281–301, (1997).

96. K. Finlay, P. R. Leavitt B. Wissel, Y. T. Prairie, Regulation of spatial and temporal variability of carbon flux in six hard-water lakes of the northern Great Plains, *Limnol. Oceanogr.* **54**, 2553–2564 (2009).

97. A. Baccini, N. Laporte, S. J. Goetz, M. Sun, H. Dong, A first map of tropical Africa’s above-ground biomass derived from satellite imagery. *Environ. Res. Lett.* **3**, 045011 (2008).

98. P. Mayaux, E. Bartholomé, S. Fritz, A. Belward, A new land-cover map of Africa for the year 2000. *J. Biogeogr.* **31**, 861–877 (2004).

99. D. Bastviken, A. L. Santoro, H. Marotta, L. Q. Pinho, D. F. Calheiros, Patrick Crill, A. Enrich-Prast, Methane emissions from Pantanal, South America, during the low water season: Toward more comprehensive sampling, *Environ. Sci. Technol.* **44**, 5450–5455 (2010).

100. P. M. Barbosa, J. M. Melack, J. H. F. Amaral, S. MacIntyre, D. Kasper, A. Cortés, V. F. Farjalla, B. R. Forsberg, Dissolved methane concentrations and fluxes to the atmosphere from a tropical floodplain lake, *Biogeochemistry* **148**, 129–151 (2020).

101. P. M. Crill, K. B. Bartlett, J. O. Wilson, D. I. Sebacher, R. C. Harriss, J. M. Melack, S. MacIntyre, L. Lesack, L. Smith-Morrill, Tropospheric methane from an Amazonian floodplain lake, *J. Geophys. Res.* **93**, 1564–1570 (1988).

102. D. Engle, J. M. Melack, Methane emissions from an Amazon floodplain lake: Enhanced release during episodic mixing and during falling water, *Biogeochemistry* **51**,71–90 (2000).

103. A. H. Devol, J. E. Richey, W. A. Clark, S. L. King, L. A. Martinelli, Methane emissions to the troposphere from the Amazon Floodplain, *J. Geophys. Res.* **93**, 1583–1592 (1988).
104. L. K. Smith, W. M. Lewis, J. P. Chanton, G. Cronin, S. K. Hamilton, Methane emissions from the Orinoco River floodplain, Venezuela. *Biogeochemistry* **51**, 113–140 (2000).

105. K. Attermeyer, S. Flury, R. Jayakumar, P. Fiener, K. Steger, V. Arya, F. Wilken, R. van Geldern, K. Premke, Invasive floating macrophytes reduce greenhouse gas emissions from a small tropical lake, *Sci. Rep.* **6**, 20424 (2016).

106. P. M. Barbosa, V. F. Farjalla, J. M. Melack, J. H. F. Amaral, J. S. da Silva, B. R. Forsberg, High rates of methane oxidation in an Amazon floodplain lake. *Biogeochemistry* **137**, 351–365 (2018).

107. R. E. Hecky, R. Mugidde, P. S. Ramlal, M. R. Talbot, G. W. Kling, Multiple stressors cause rapid ecosystem change in Lake Victoria. *Freshw. Biol.* **55**, 19–42 (2010).

108. P. M. Barbosa, J. M. Melack, V. F. Farjalla, J. H. F. Amaral, V. Scofield, B. R. Forsberg, Diffusive methane fluxes from Negro, Solimões and Madeira rivers and fringing lakes in the Amazon basin. *Limnol. Oceanogr.* **61**, S221–S237 (2016).

109. G. Abril, J.-M. Martinez, L. F. Artigas, P. Moreira-Turcq, M. F. Benedetti, L. Vidal, T. Meziane, J.-H. Kim, M. C. Bernardes, N. Savoye, J. Deborde, P. Albéric, M. F. L. Souza, E. L. Souza, F. Roland, Amazon river carbon dioxide outgassing fuelled by wetlands, *Nature* **505**, 395–398 (2014).

110. B. Panneer Selvam, S. Nachimuthu, L. Arunachalam, D. Bastviken, Methane and carbon dioxide emissions from inland waters in India - implications for large scale greenhouse gas balances. *Glob. Change Biol.* **20**, 3397–3407 (2014).

111. M. U. Mendoza-Pascual, M. Itoh, J. I. Aguilar, K. S. A. R. Padilla, R. D. S. Papa, N. Okuda, Controlling factors of methane dynamics in tropical lakes of different depths. *J. Geophys. Res. Biogeosci.* **126**, e2020JG005828 (2021).

112. D. Tonetta, P. A. Staehr, B. Obrador, L. P. Mello Brandão, L. Silva Brighenti, M. Mello Petrucio, F. A. Rodrigues Barbosa, J. F. Bezerra-Neto, Effects of nutrients and organic matter inputs in the gases CO$_2$ and O$_2$: A mesocosm study in a tropical lake, *Limnologica* **69**, 1–9 (2018).
113. P. A. Macklin, I. G. N. A. Suryaputra, D. T. Maher, I. R. Santos, Carbon dioxide dynamics in a lake and a reservoir on a tropical island (Bali, Indonesia). *PLOS ONE* 13, e0198678 (2018).

114. P. Albéric, M. A. P. Pérez, P. Moreira-Turcq, M. F. Benedetti, S. Bouillon, G. Abril, Variation of the isotopic composition of dissolved organic carbon during the runoff cycle in the Amazon River and the floodplains. *C. R. Geosci.* 350, 65–75 (2018).

115. J. H. F. Amaral, J. M. Melack, P. M. Barbosa, S. MacIntyre, D. Kasper, A. Cortés, T. S. Freire Silva, R. Nunes de Sousa, B. R. Forsberg, Carbon dioxide fluxes to the atmosphere from waters within flooded forests in the Amazon basin. *J. Geophys. Res. Biogeosci.* 125, e2019JG005293 (2020).

116. M. Call, C. J. Sanders, A. Enrich-Prast, L. Sanders, H. Marotta, I. R. Santos, D. T. Maher, Radon-traced pore-water as a potential source of CO₂ and CH₄ to receding black and clear water environments in the Amazon Basin, *Limnol. Oceanogr. Lett.* 3, 375–383 (2018).

117. S. Sobek, L. J. Tranvik, Y. P. Prairie, P. Kortelainen, J. J. Cole Patterns and regulation of dissolved organic carbon: An analysis of 7,500 widely distributed lakes. *Limnol. Oceanogr.* 52, 1208–1219 (2007).

118. M. Frankignoulle, A. Borges, R. Biondo, A new design of equilibrator to monitor carbon dioxide in highly dynamic and turbid environments. *Water Res.* 35, 1344–1347 (2001).

119. G. W. Kling, M. A. Clark, G. N. Wagner, H. R. Compton, A. M. Humphrey, J. D. Devine, W. C. Evans, J. P. Lockwood, M. L. Tuttle, E. J. Koenigsberg, The 1986 Lake Nyos gas disaster in Cameroon, West Africa. *Science* 236, 169–175 (1987).