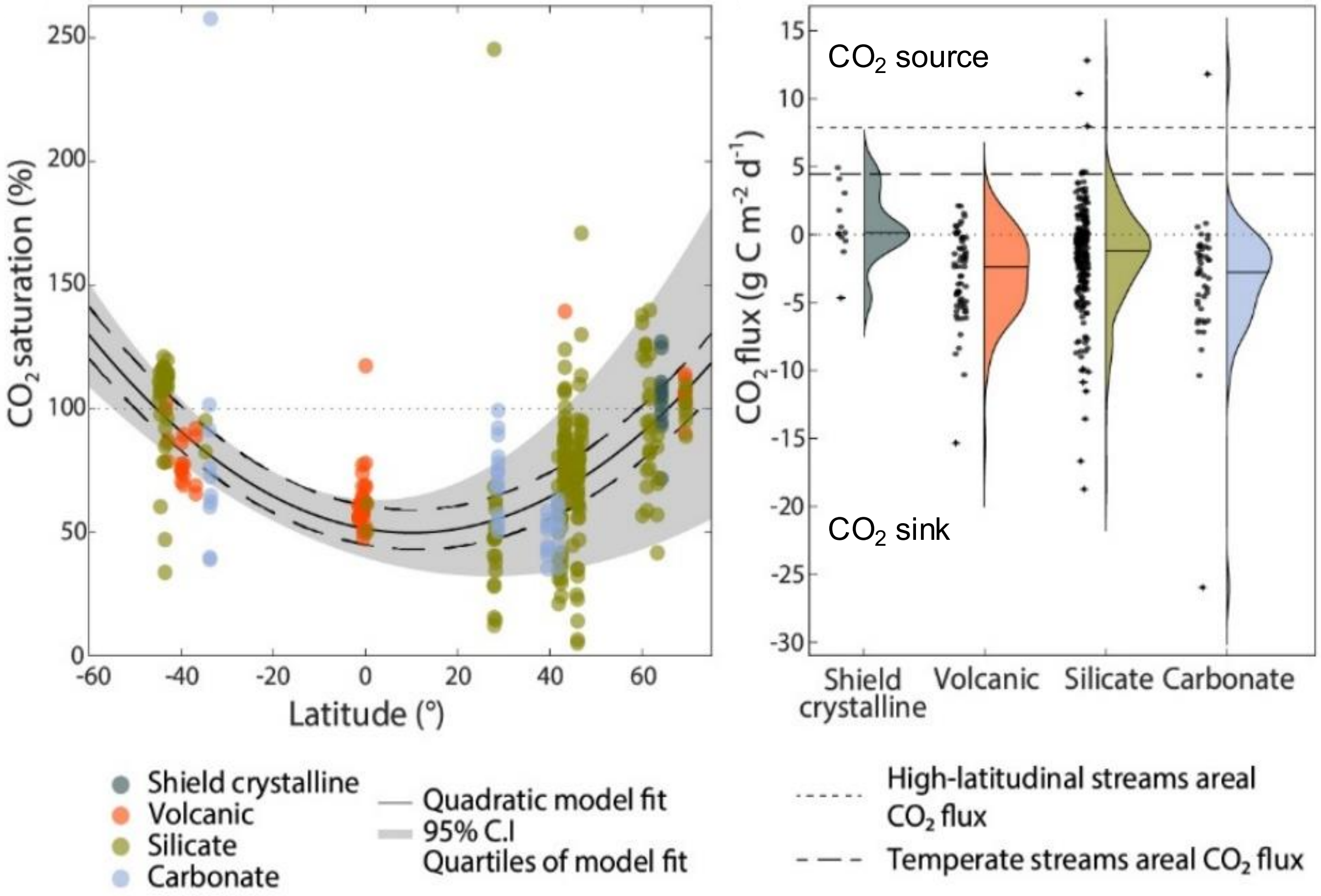
# Most streams are $CO_2$ emittors, but not all!

EPFL

# Glacier-fed streams and lakes

- Glacier-fed streams are $CO_2$ sinks depending on parent geology
- Chemical weathering consumes $CO_2$
- Likely in equilibrium with the atmosphere before industrialisation




*Styllas et al. in review*

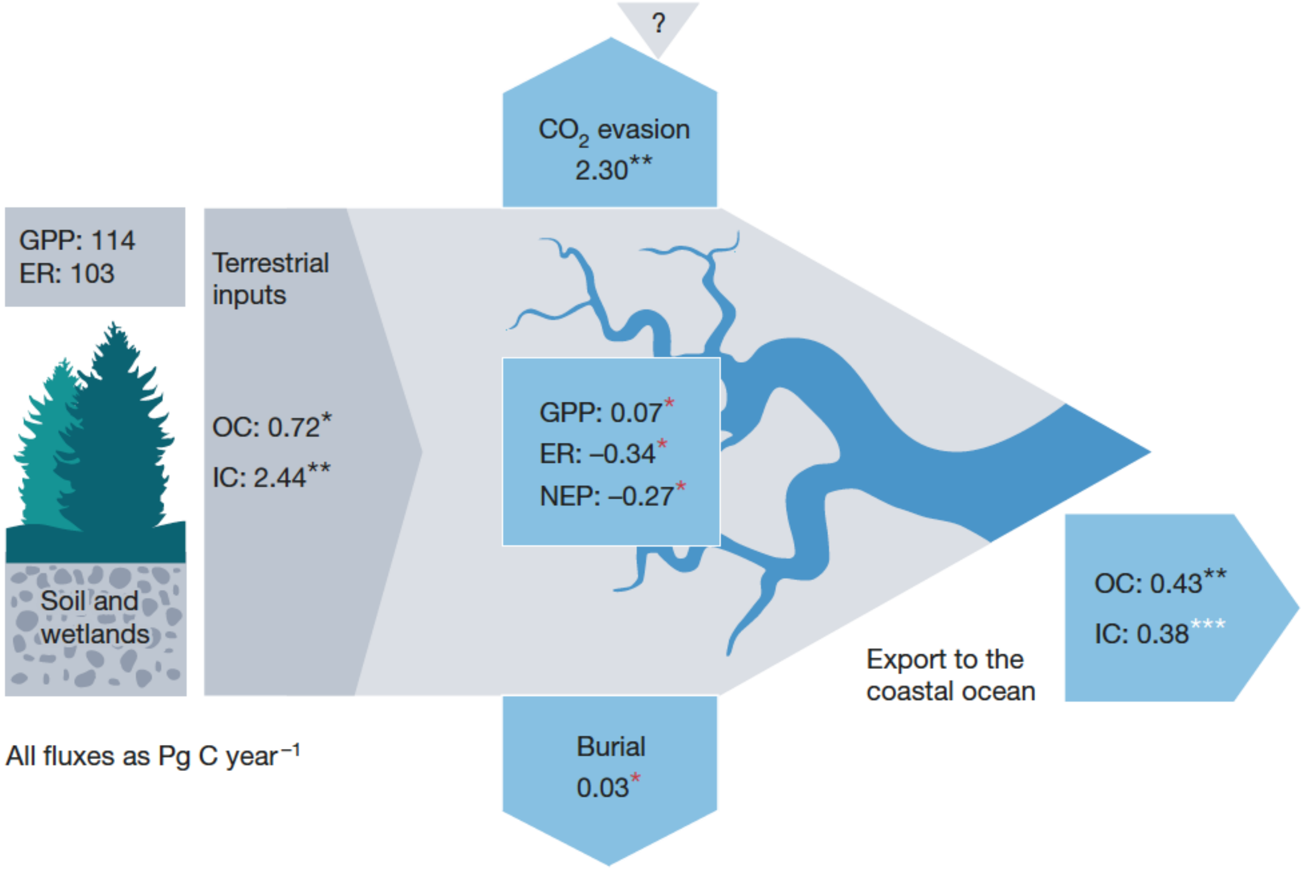
# Streams and rivers are major components of the global

Review

## River ecosystem metabolism and carbon biogeochemistry in a changing world

https://doi.org/10.1038/s41586-022-05500-8
Received: 12 March 2021
Accepted: 31 October 2022

Tom J. Battin[1✉], Ronny Lauerwald[2], Emily S. Bernhardt[3], Enrico Bertuzzo[4], Lluís Gómez Gener[5], Robert O. Hall Jr[6], Erin R. Hotchkiss[7], Taylor Maavara[8], Tamlin M. Pavelsky[9], Lishan Ran[10,11], Peter Raymond[12], Judith A. Rosentreter[12,13] & Pierre Regnier[14]




- $CO_2$ emissions from streams and rivers similar to the drawdown fluxes of atmospheric $CO_2$ by the world's oceans
- Ecosystem metabolism contributes ca.10% to global $CO_2$ emissions – up to 90% locally.
- Remaining $CO_2$ from terrestrial primary production and chemical weathering

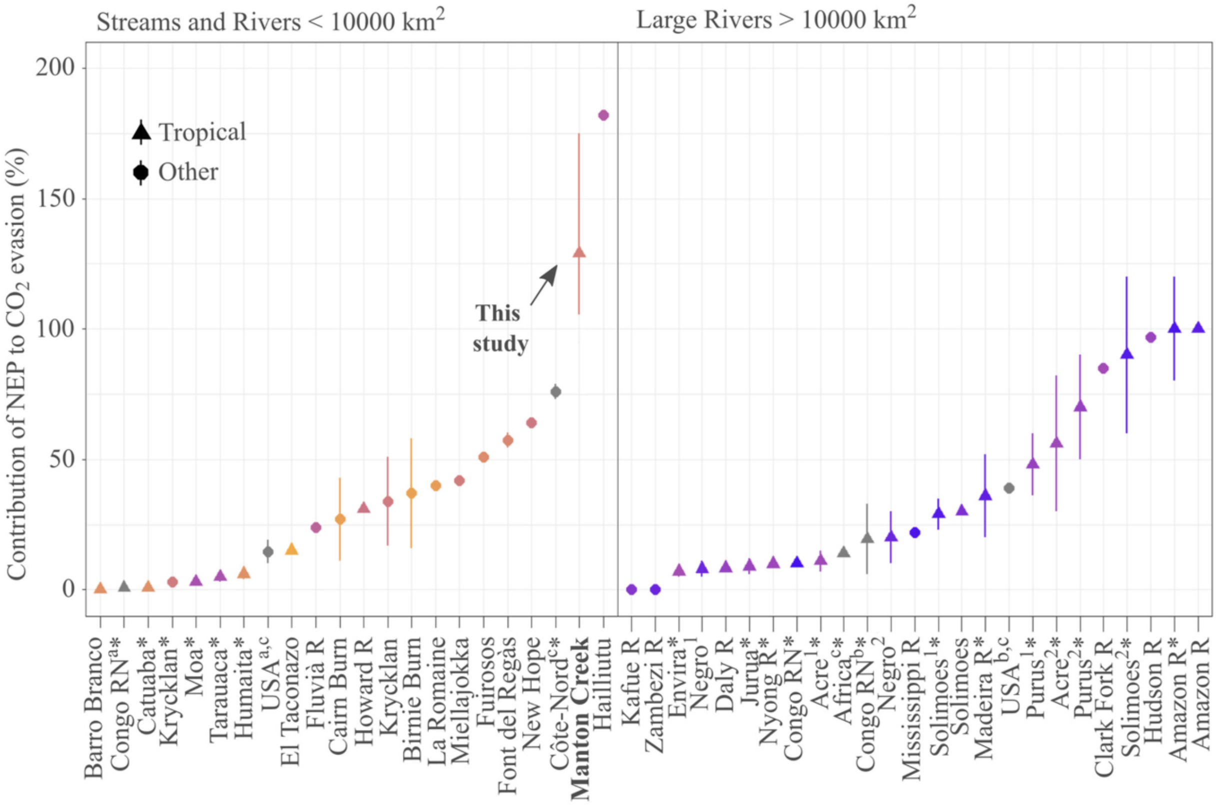
# River networks matter for the global carbon cycle

LIMNOLOGY and OCEANOGRAPHY
ASLO
Limnol. Oceanogr. 9999, 2023, 1–15
doi: 10.1002/lno.12334


**Stream respiration exceeds $CO_2$ evasion in a low-energy, oligotrophic tropical stream**

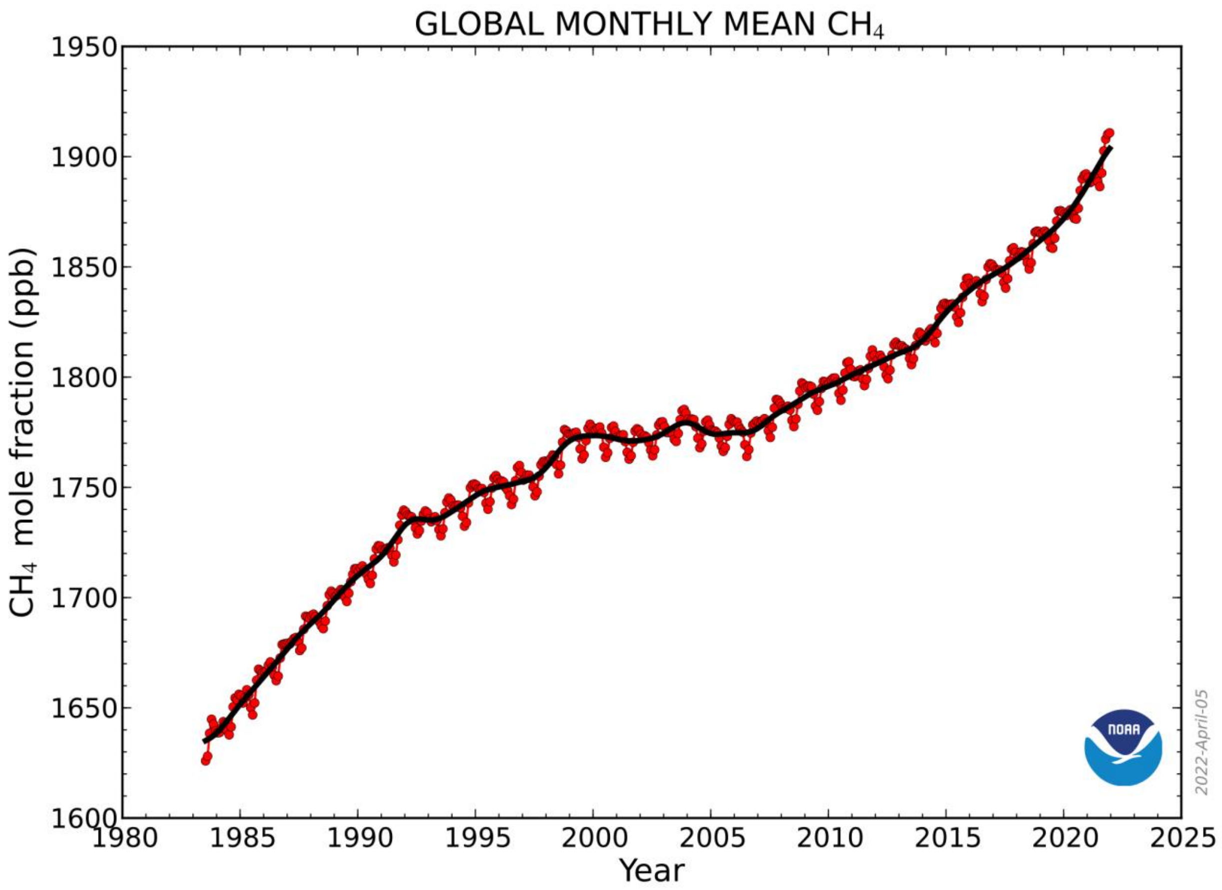
Vanessa Solano[1*] Clément Duvert[1,2*] Christian Birkel[3,4] Damien T. Maher[5] Erica A. García[1]
Lindsay B. Hutley[1]

- Contributions from river NEP to $CO_2$ evasion from rivers vary widely
- Depend on gas exchange rate, carbonate dissolution, photochemistry etc

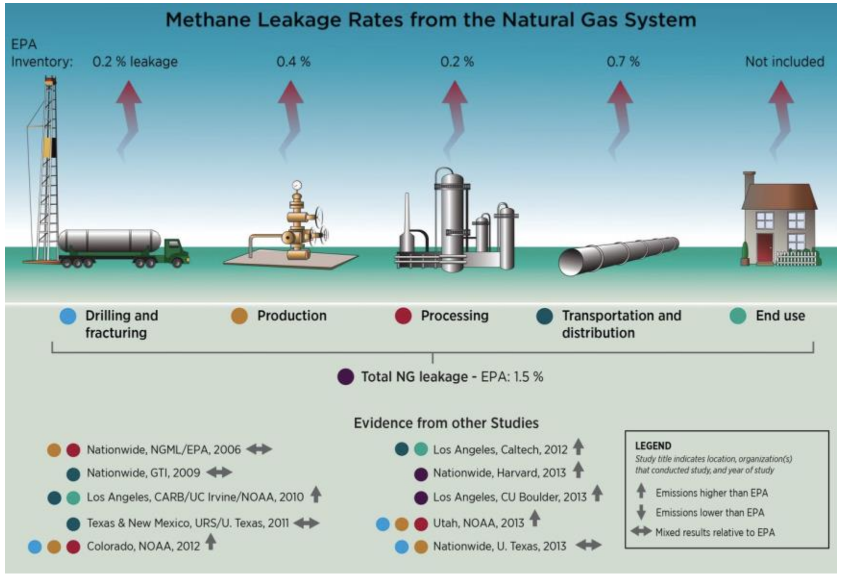


## What about methane?

Biological sources (methanogenesis by archaea and bacteria)
Geogenic sources
Anthropogenic sources




- Methane is a potent greenhouse gas
- Its emissions are globally increasing at a rapid pace




Leaky gas infrastructures as one major source of methane to the atmosphere

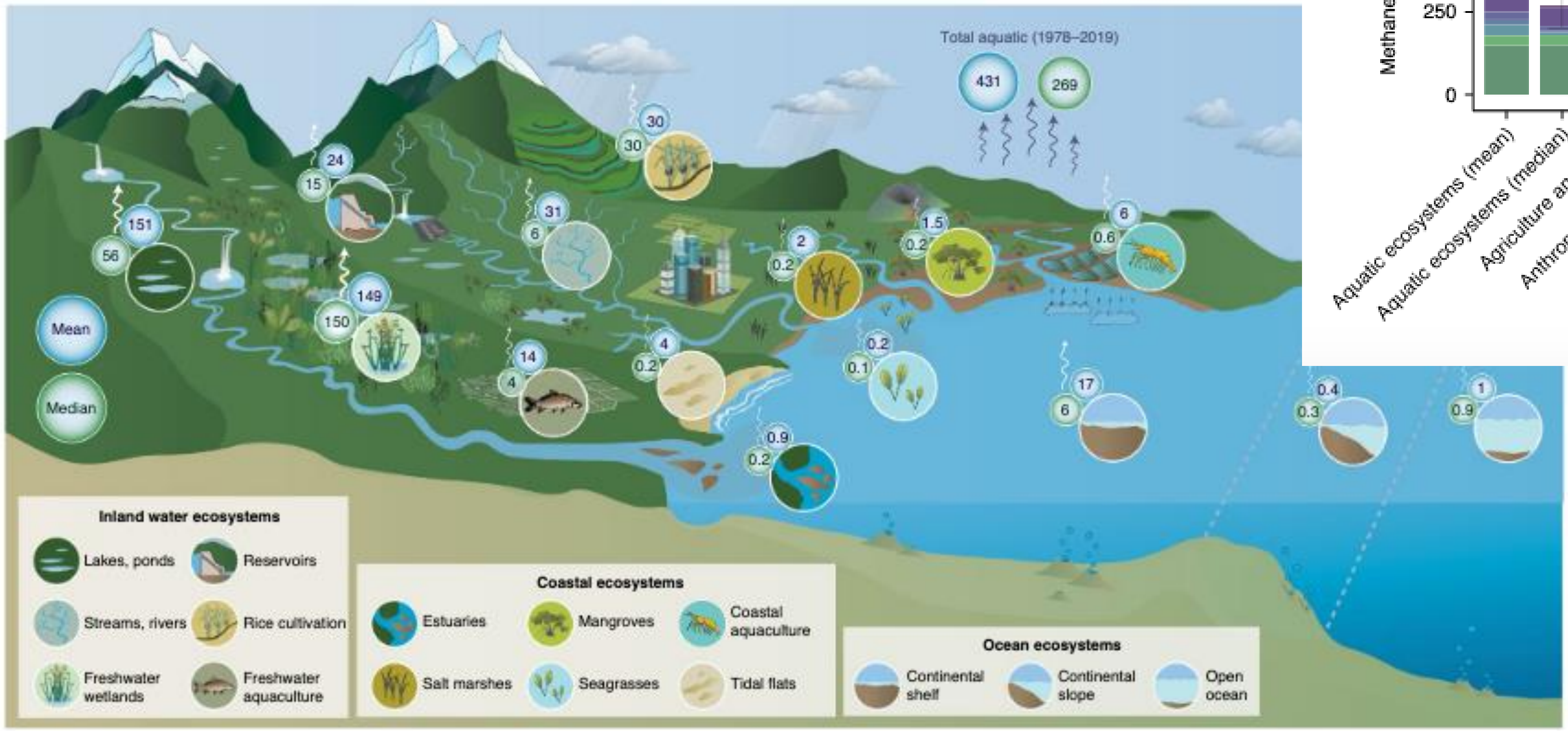
…what else?

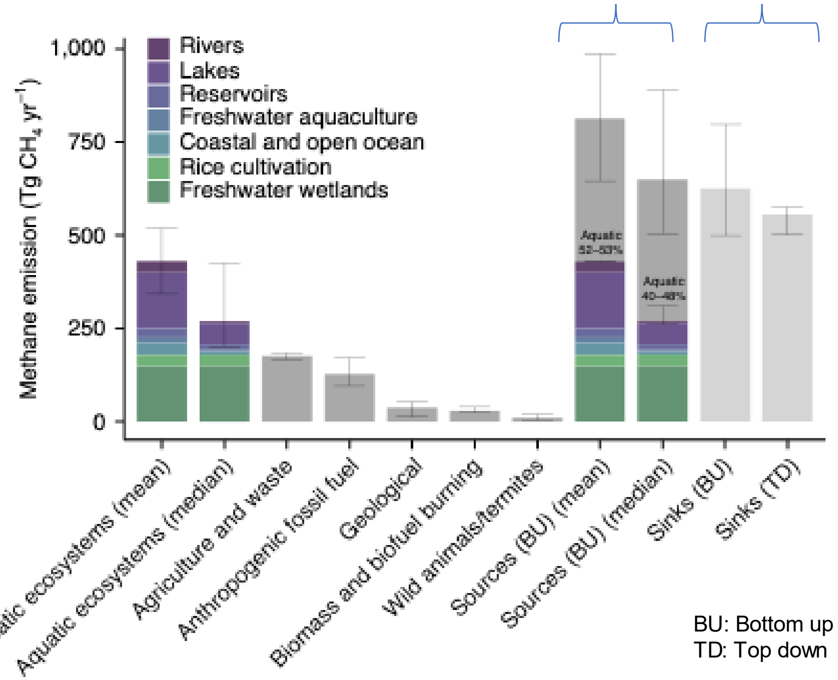
# Streams and rivers are major sources of methane to the atmosphere

nature geoscience
ARTICLES
https://doi.org/10.1038/s41561-021-00715-2
Check for updates

## Half of global methane emissions come from highly variable aquatic ecosystem sources

Judith A. Rosentreter[1,2], Alberto V. Borges[3], Bridget R. Deemer[4], Meredith A. Holgerson[5,6,7], Shaoda Liu[2,8], Chunlin Song[9,10], John Melack[11], Peter A. Raymond[2], Carlos M. Duarte[12,13], George H. Allen[14], David Olefeldt[15], Benjamin Poulter[16], Tom I. Battin[17] and Bradley D. Eyre[1]




BU: Bottom up
TD: Top down

**Fig. 3 | Global aquatic methane emissions from headwater streams to the open ocean.** Numbers are Tg $CH_4$ $yr^{-1}$. Mean emissions are shown in blue circles, and median emissions are shown in green circles. The relative importance of the factors controlling methane distribution and emissions varies along the land–ocean aquatic continuum.

$1 Tg = 10^{12}$ g

EPFL

Article

# Global methane emissions from rivers and streams

https://doi.org/10.1038/s41586-023-06344-6

Received: 25 October 2022

Gerard Rocher-Ros[1,2,3]✉, Emily H. Stanley[4], Luke C. Loken[5], Nora J. Casson[6], Peter A. Raymond[7], Shaoda Liu[7,8], Giuseppe Amatulli[7] & Ryan A. Sponseller[1]

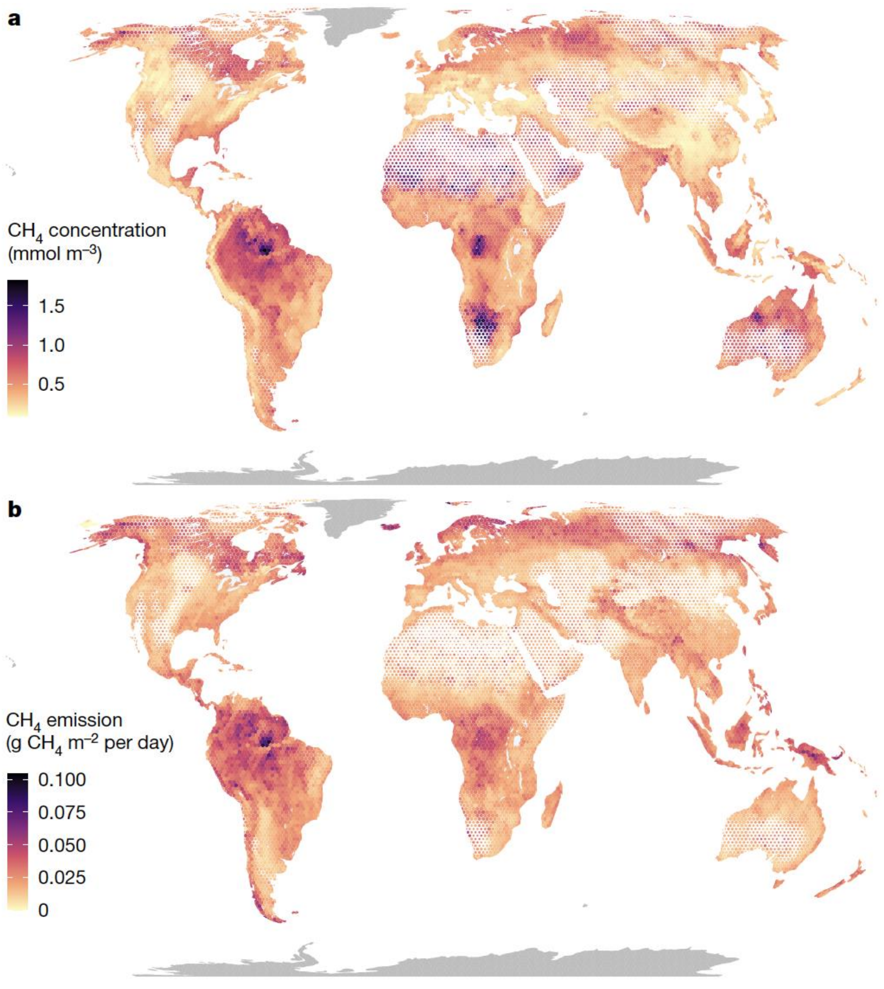



**Fig. 1 | Global patterns of $CH_4$ in rivers and streams. a,b**, Modelled yearly average $CH_4$ concentrations (**a**) and emissions (**b**) in rivers and streams. Data have been aggregated in hexagonal bins, and the size of each hexagon is rescaled with runoff, to better visualize patterns in areas with high coverage of running waters. Areas with runoff greater than 1,500 mm per year have full-sized hexagons; hexagons in areas with runoff of 500 mm per year have been reduced by 10%; and hexagons with a runoff less than 50 mm per year have been reduced by 50%. The model could not be applied in Greenland and Antarctica, which are shown in dark grey.

- Streams and rivers emit 27.9 (16.7–39.7) Tg $CH_4$ per year, roughly equal emissions from lakes and ponds
- Physical ecosystem attributes and land use as some of the best predictors for $CH_4$ concentrations

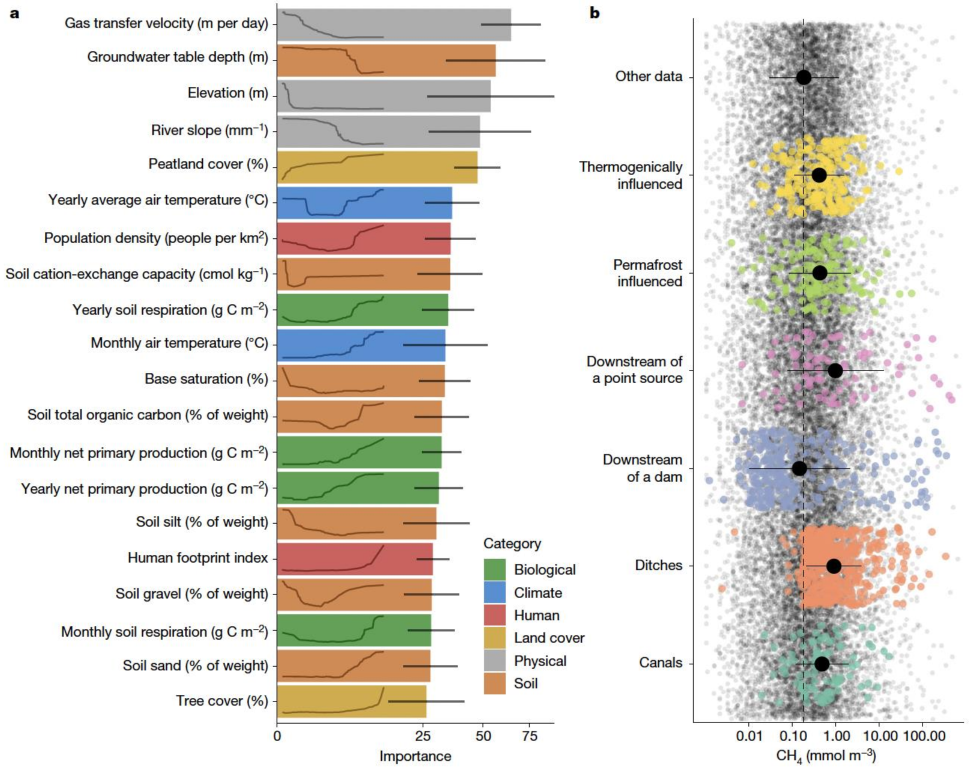



**Fig. 2 | Main drivers of $CH_4$ concentrations in streams. a**, The 20 most important variables in the random forest model. The *x* axis shows the median importance across all monthly models ($n = 12$), with error lines representing standard deviation (s.d.); note the square-root transformation of the *x* axis. The line inside each bar is the partial dependence, which represents the marginal effect of a given feature (*x* axis) on predicted $CH_4$ concentrations (*y* axis). These lines are a simplification of a more detailed version (Supplementary Information). **b**, $CH_4$ concentrations of some site categories from GRiMeDB[13] were excluded from the model as they were not captured in the hydrological model or were targeted observations not representative of catchment properties (Methods). The underlying jittered points represent all other observations in GRiMeDB, with the dashed line representing the average. Each category is colour-coded, with the black dot and a line representing the mean ± s.d.

Article

# Global methane emissions from rivers and streams

https://doi.org/10.1038/s41586-023-06344-6
Received: 25 October 2022

Gerard Rocher-Ros[1,2,3]✉, Emily H. Stanley[4], Luke C. Loken[5], Nora J. Casson[6], Peter A. Raymond[7], Shaoda Liu[7,8], Giuseppe Amatulli[7] & Ryan A. Sponseller[1]

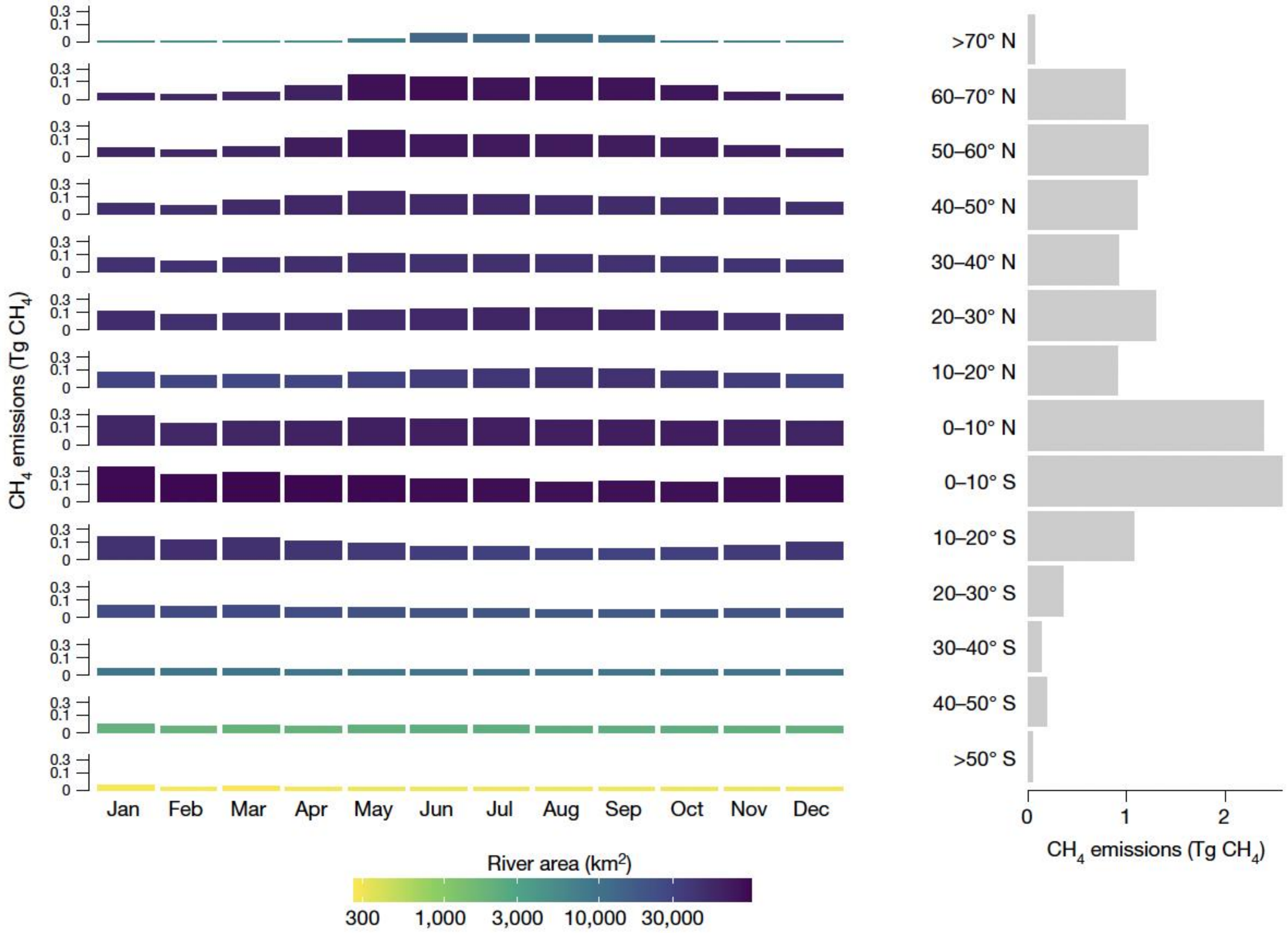
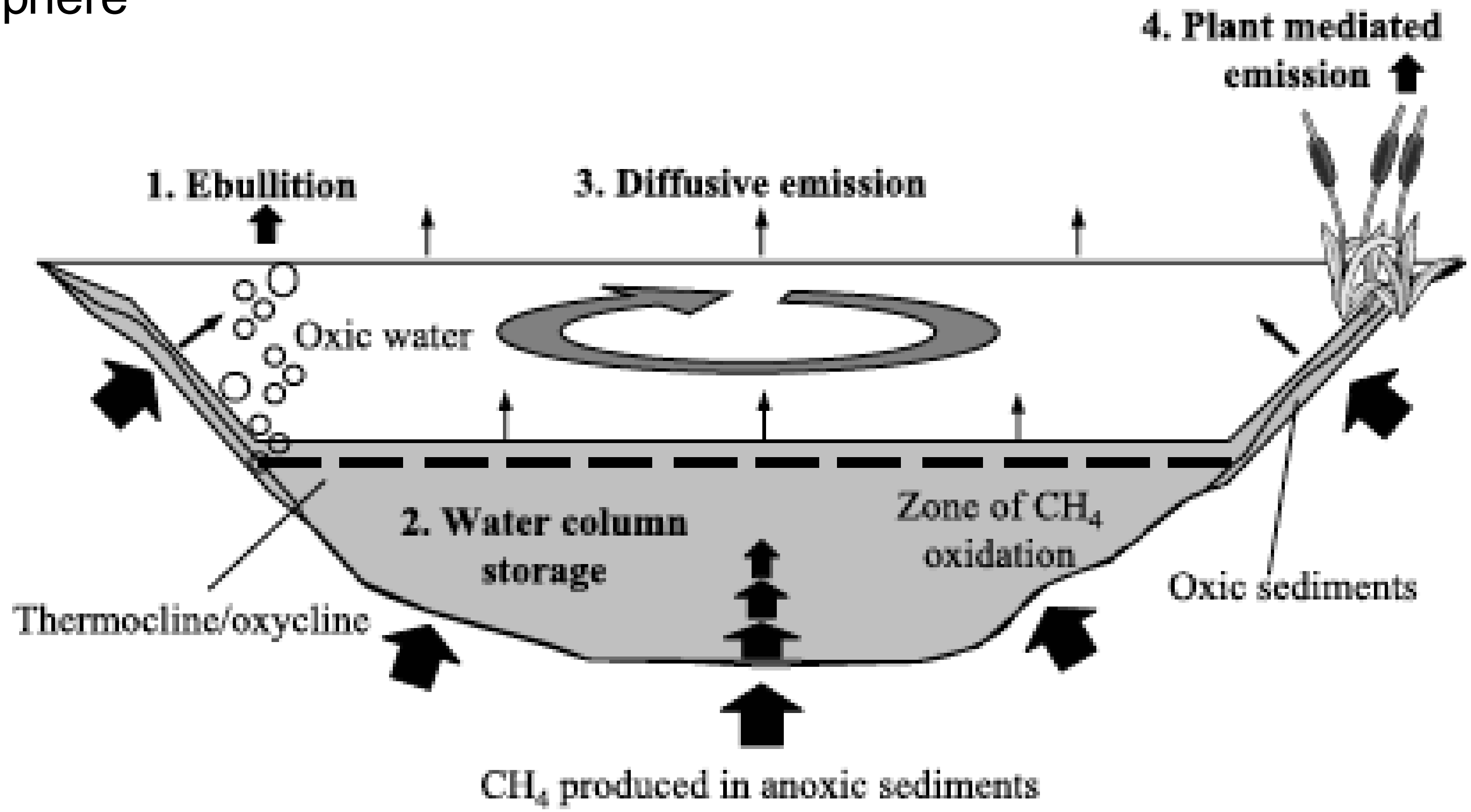



**Fig. 3 | Seasonal patterns of $CH_4$ emissions.** Left: total monthly $CH_4$ emissions for each latitudinal band (10° bins), with the colour representing total river area. Right: total yearly emissions for each latitudinal band. In the left panel, the *y* axis is square-root transformed, and the colour scale is log transformed.

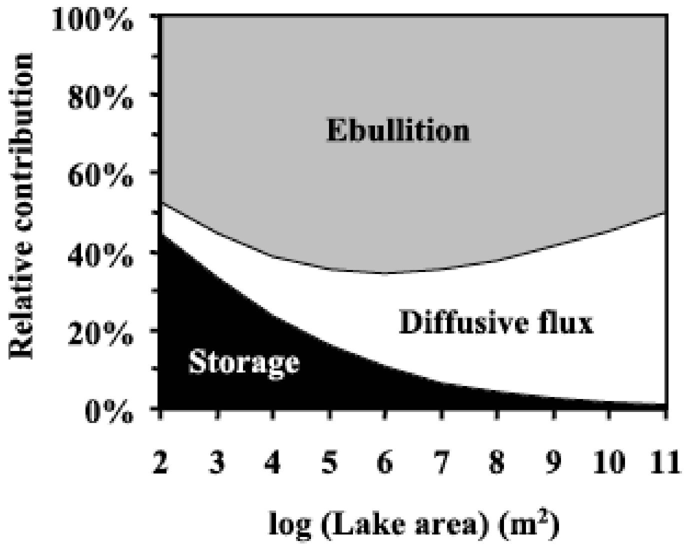
- Clear seasonal and latitudinal patterns of $CH_4$ emissions
- Important to account for temporal and spatial variation of $CH_4$ emissions when scaling up to the global scale

# Transportation of methane from aquatic ecosystems

Ebullition is the major transportation path from sediments to the water and atmosphere




Methanogenesis
in anoxic sediments




Bastviken et al. 2004 GBC

# Hydropower reservoirs emit greenhouse gases

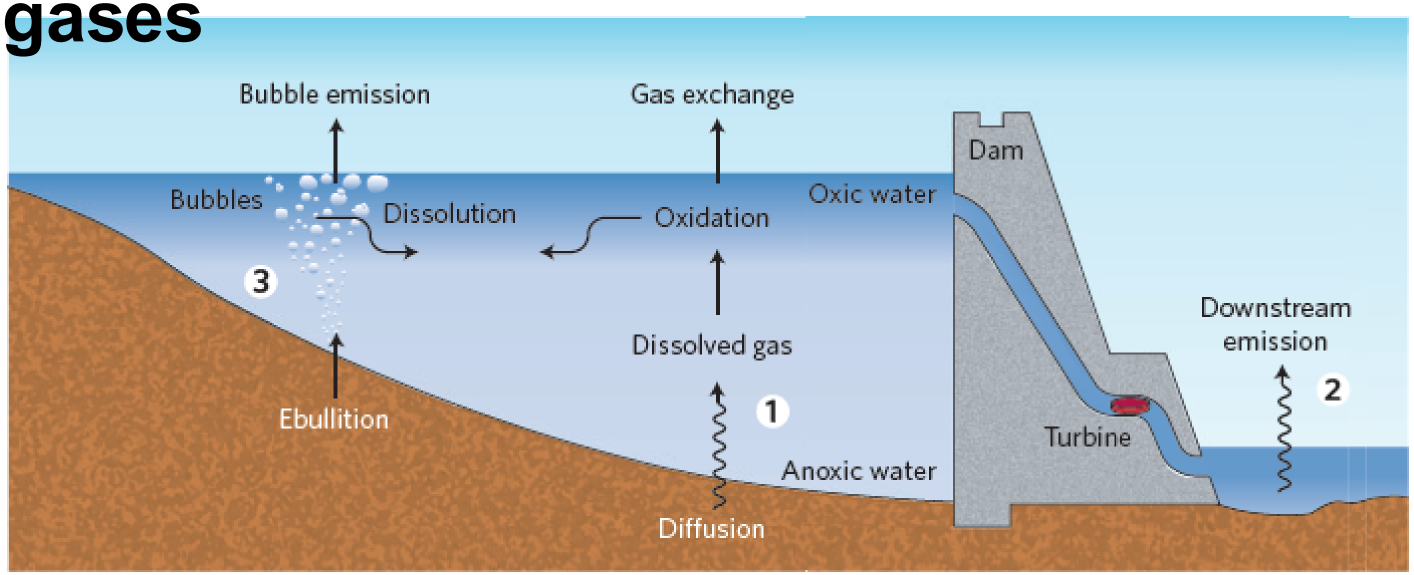



**Figure 1 |** Schematic methane emission pathways from a hydroelectric reservoir. In sediments with slower methane formation and at greater depths, dissolved methane diffuses upwards (1). The methane enters the atmosphere through gas exchange at the surface. Emissions may be reduced by microbial oxidation at the interface between the oxic and anoxic water layers. Second, downstream emissions after the water has passed the turbine (2) depend on the stratification of the reservoir and the vertical position of the main water intake. Finally, in sediments with high methane production rate, bubbles form when the methane solubility is exceeded (3). Some of this methane dissolves from the rising bubbles but a large fraction is rapidly emitted to the atmosphere. Barros and colleagues[3] estimate emissions of carbon dioxide and methane from 85 hydroelectric reservoirs worldwide, but because the third pathway is poorly constrained by measurements, uncertainties remain large.

Wehrli 2011 Nature Geoscience

# The contribution of dams to $CH_4$ production and outgassing


Del Sontro et al. 2010 ES&T

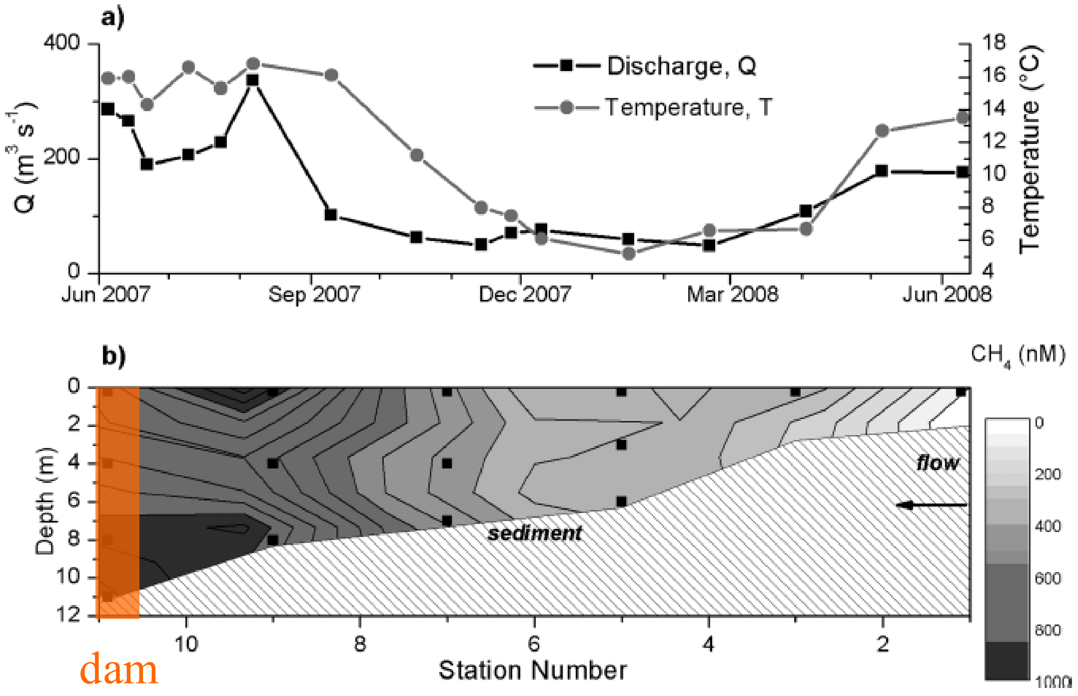
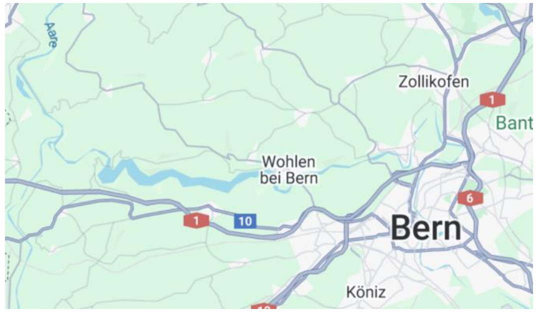



FIGURE 1. a) Temperature and discharge, *Q*, in Lake Wohlen during samplings. *Q* ranges from ~400 $m^3$ $s^{-1}$ in summer (residence time, Rt, ~1 day) to 50 $m^3$ $s^{-1}$ in winter (Rt ~7 days). b) Contour plot of dissolved methane distribution in Lake Wohlen on June 21, 2007. Black squares - actual samplings. Water flows in from right to the dam (left). Profiles were taken every kilometer at a vertical resolution of 3–4 m. The figure suggests that methane is vertically homogeneous, while concentrations can increase five times horizontally.

$CH_4$ can accumulate in reservois towards the dam

# The contribution of dams to $CH_4$ production and outgassing




Del Sontro et al. 2010 ES&T

Model including ebullition & temperature

total

ebullition

diffusion

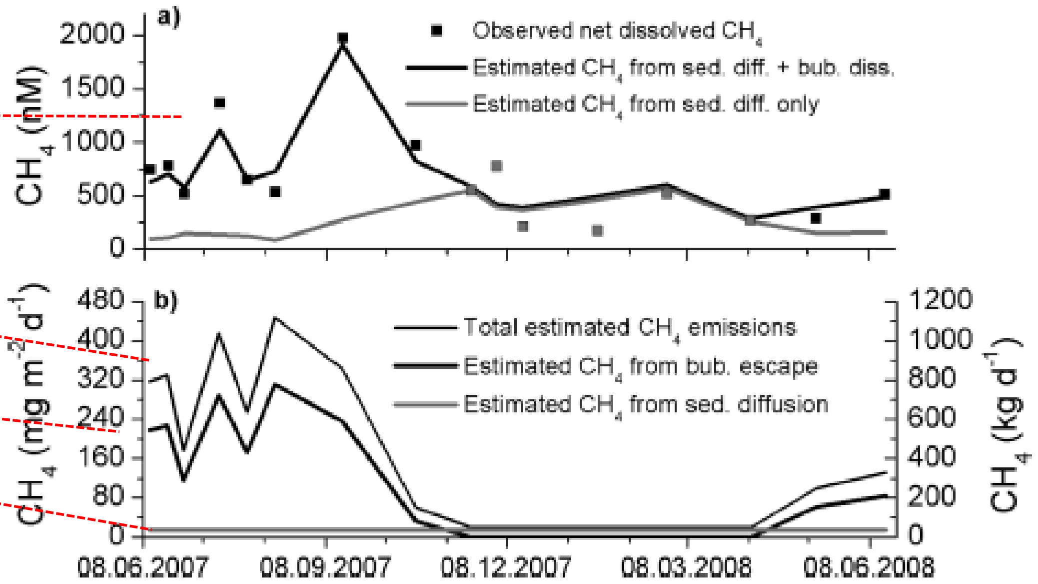
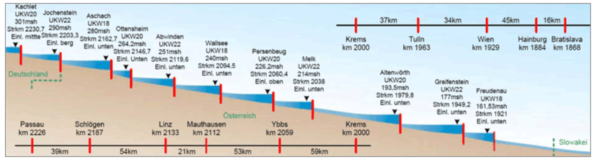



**FIGURE 3. Lake Wohlen system analysis results. a) Squares indicate measured dissolved methane in Lake Wohlen (outflow - inflow). Black squares indicate measurements at water temperatures, $T > 10$ °C when ebullition is occurring, gray squares when $T < 10$ °C (see Figure 2). Gray line - best fit of predicted concentration due to sediment diffusion (sed. diff.) only. Black line - model results for predicted $CH_4$ concentration using exponential fit for methane bubble dissolution (bub. diss.) as a function of temperature plus the constant sediment diffusion of 15 mg $m^{-2}$ $day^{-1}$ (Figure 2). b) $CH_4$ emission rates: Gray line - constant sediment diffusion input. Thick black line - predicted methane emission due to methane bubbles reaching the atmosphere (bub. escape). Thin black line - total predicted methane flux including dam discharge emissions.**

Evasion flux: 150 mg $CH_4$ $m^{-2}$ $d^{-1}$

- Ebullition dominates the $CH_4$ evasion from Lake Wohlen reservoire.
- Indicative of high $CH_4$ production rates in the acculmulated sediments.




- Even low-land rivers with hydraulic constructions are sources of $CH_4$
- Sediment accumulation and elevated $CH_4$ production upriver from watergates for navigation

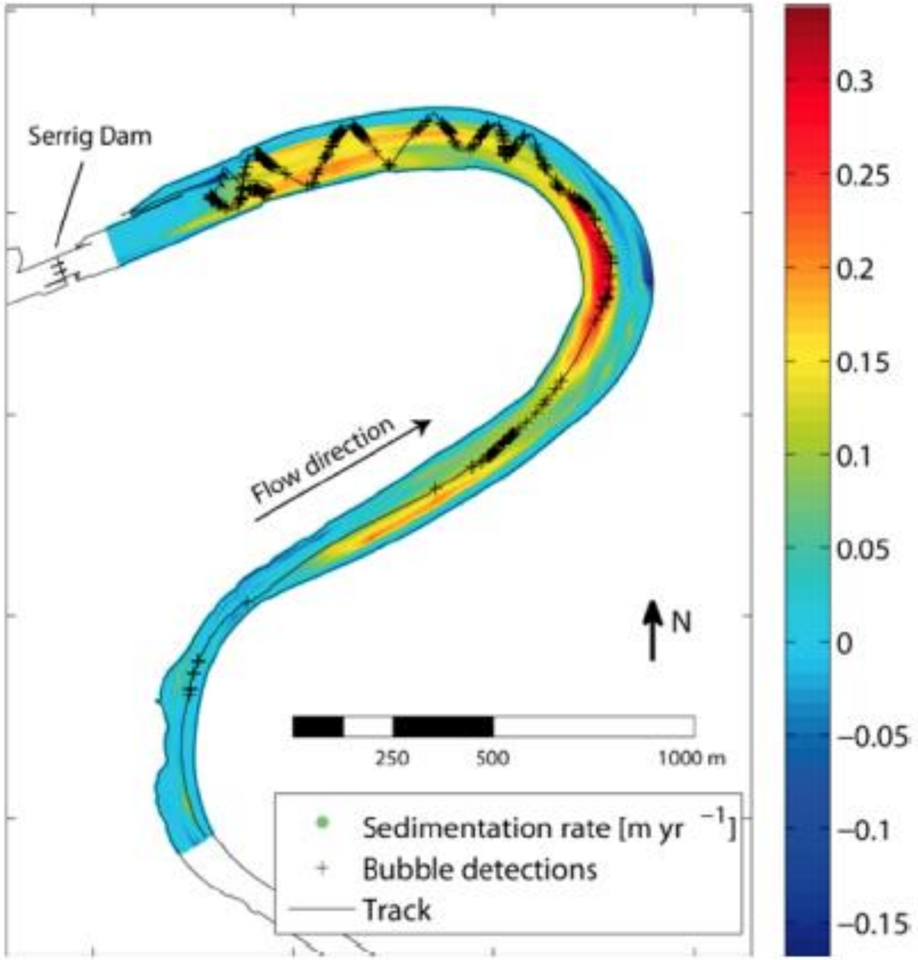
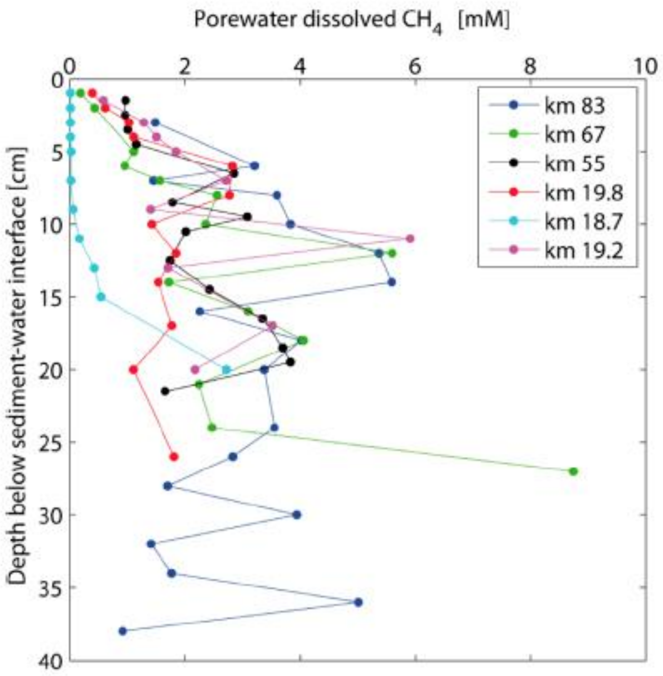



**Figure 2.** Mean sediment accumulation rate between 1993 and 2010 (color scaling) and bubble detections in the forebay of Serrig dam. Crosses mark bubble detection along the sampling transect, which is denoted by the black line.

Maeck et al. 2013 *ES&T*



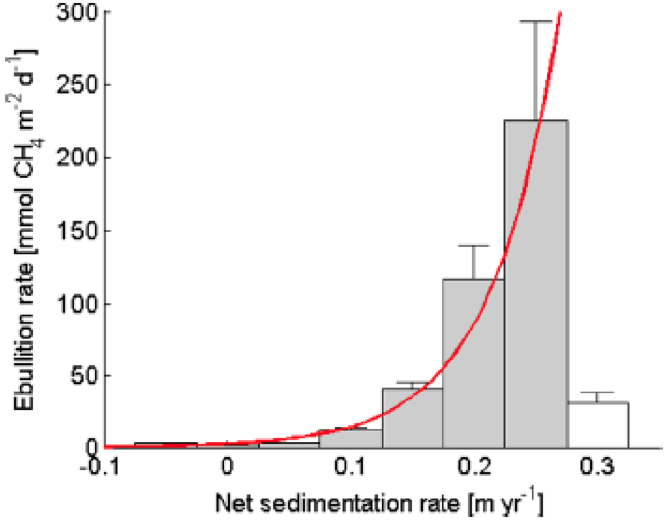




**Figure 4.** Relationship between sediment accumulation rate (1993–2010) and measured ebullition rates. The red line shows the exponential fit ($R^2 = 0.91$; $p < 0.001$; $n = 7$). The white bar at 0.3 was excluded from the analysis due to its small sample size. Error bars denote the standard error of mean.

Maeck et al. 2013 *ES&T*

Reaches with elevated sediment accumulation are hotspots of $CH_4$ production and ebullition in rivers

EPFL

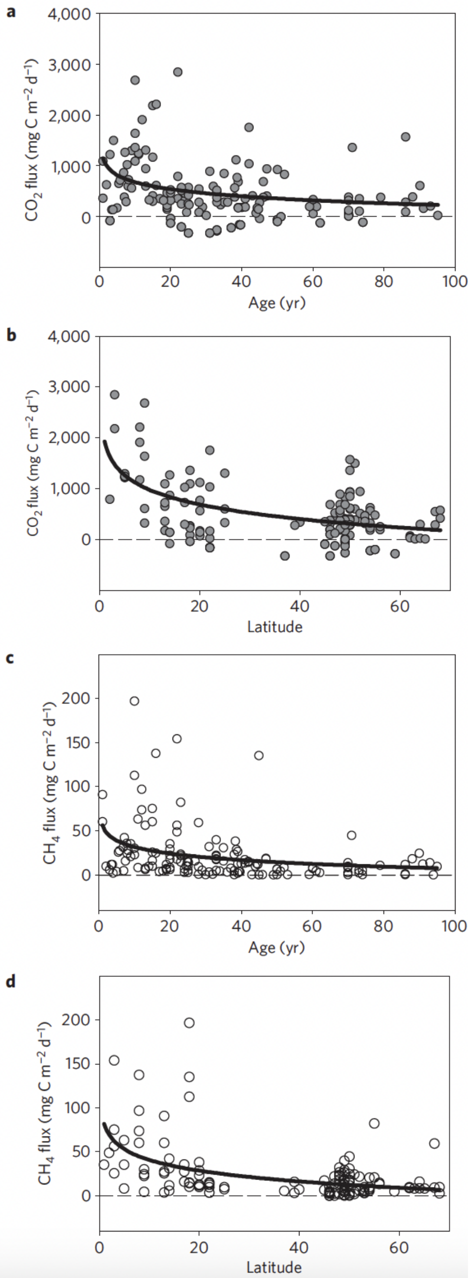
nature geoscience
LETTERS
PUBLISHED ONLINE: 31 JULY 2011 | DOI:10.1038/NGEO1211

## Carbon emission from hydroelectric reservoirs linked to reservoir age and latitude

Nathan Barros[1], Jonathan J. Cole[2], Lars J. Tranvik[3], Yves T. Prairie[4], David Bastviken[5], Vera L. M. Huszar[6], Paul del Giorgio[4] and Fábio Roland[1]*

- GHG emissions from reservoirs changing with latitude and age
- Highest in the Amazonas
- Topography, temperature and flooded biomass

Petit Saut Reservoir French Guyane



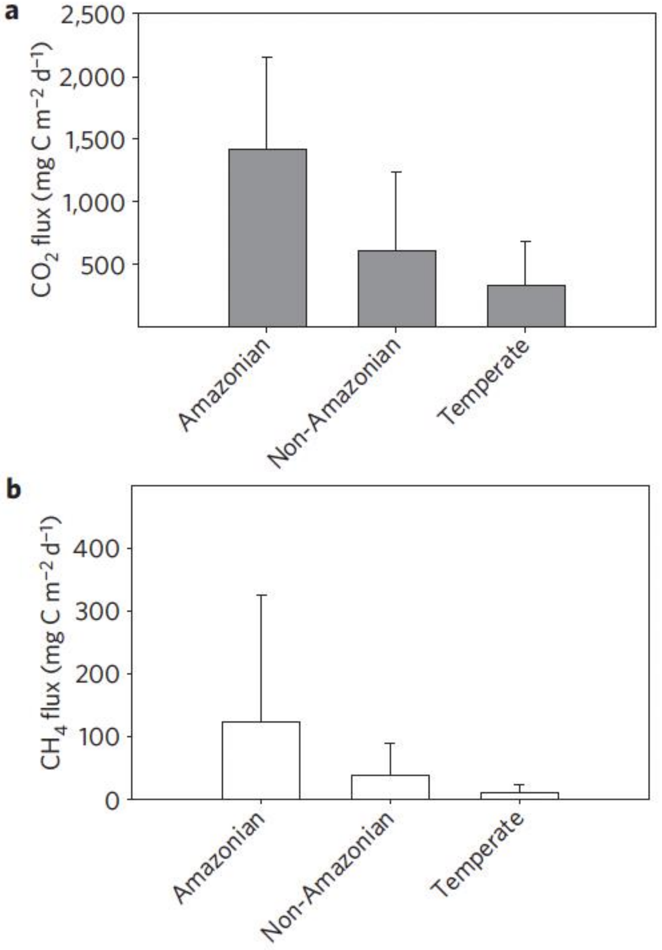




**Figure 2 | Fluxes of $CO_2$ and $CH_4$ in different zones.** Mean (bars) and standard deviation (lines) of the **a**, $CO_2$ and **b**, $CH_4$ fluxes in the 85 hydroelectric reservoirs worldwide distributed clustered by region. The tropical region was split into Amazonian and non-Amazonian regions.

# Greenhouse Gas Emissions from Reservoir Water Surfaces: A New Global Synthesis

BRIDGET R. DEEMER, JOHN A. HARRISON, SIYUE LI, JAKE J. BEAULIEU, TONYA DELSONTRO, NATHAN BARROS, JOSÉ F. BEZERRA-NETO, STEPHEN M. POWERS, MARCO A. DOS SANTOS, AND J. ARIE VONK

- Reservoirs are significant emittors of greenhouse gases ($CH_4$, $CO_2$ and $N_2O$) to the atmosphere
- Degradation of flooded biomass
- Degradation of accumulating organic matter in the sediments
- Increased temperature and primary production

How carbon-free is hydropower?

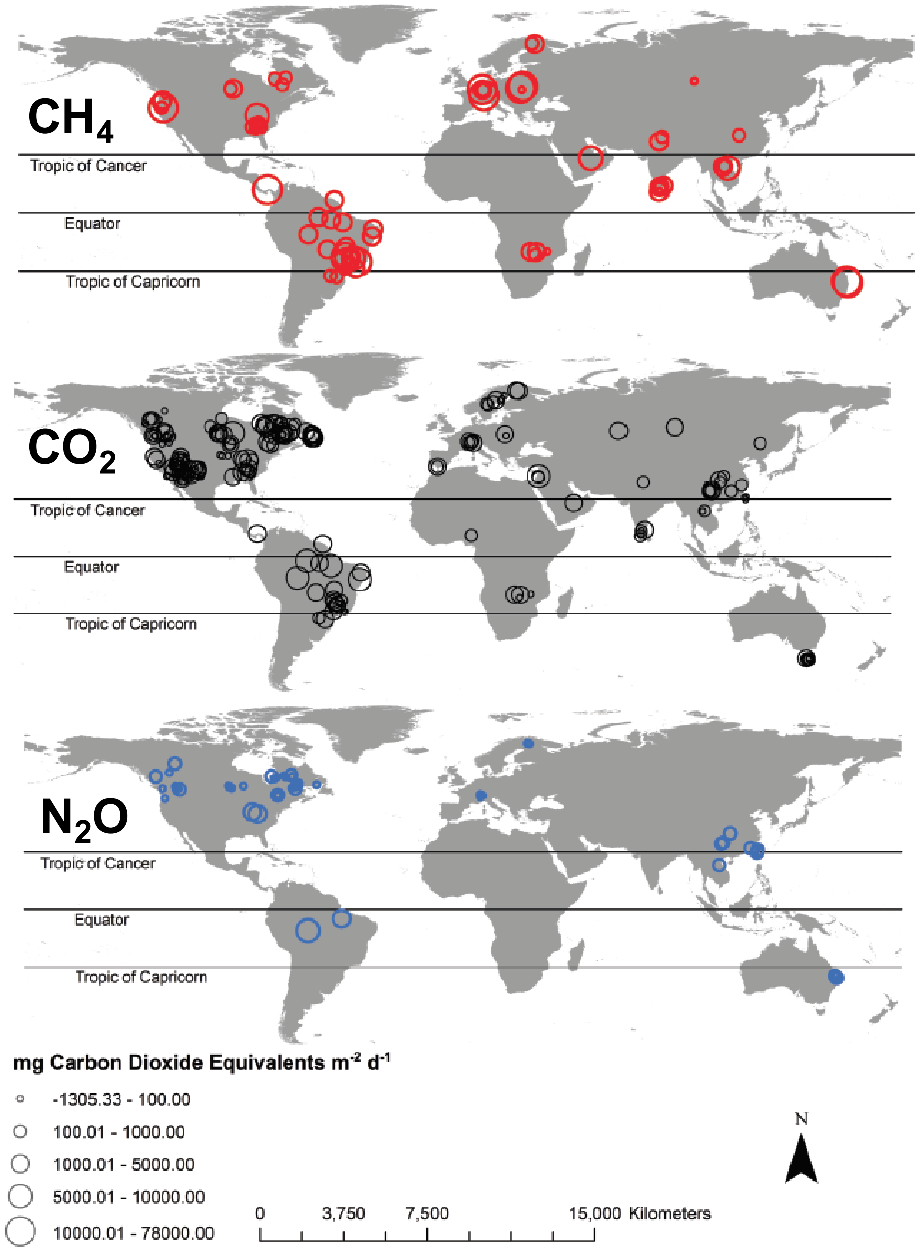



*Figure 2. Diffusive + ebullitive methane (top), carbon dioxide (middle), and nitrous oxide (bottom) emissions from reservoirs on a $CO_2$-equivalent basis (100-year horizon). Few reservoirs had measurements for all three gases.*

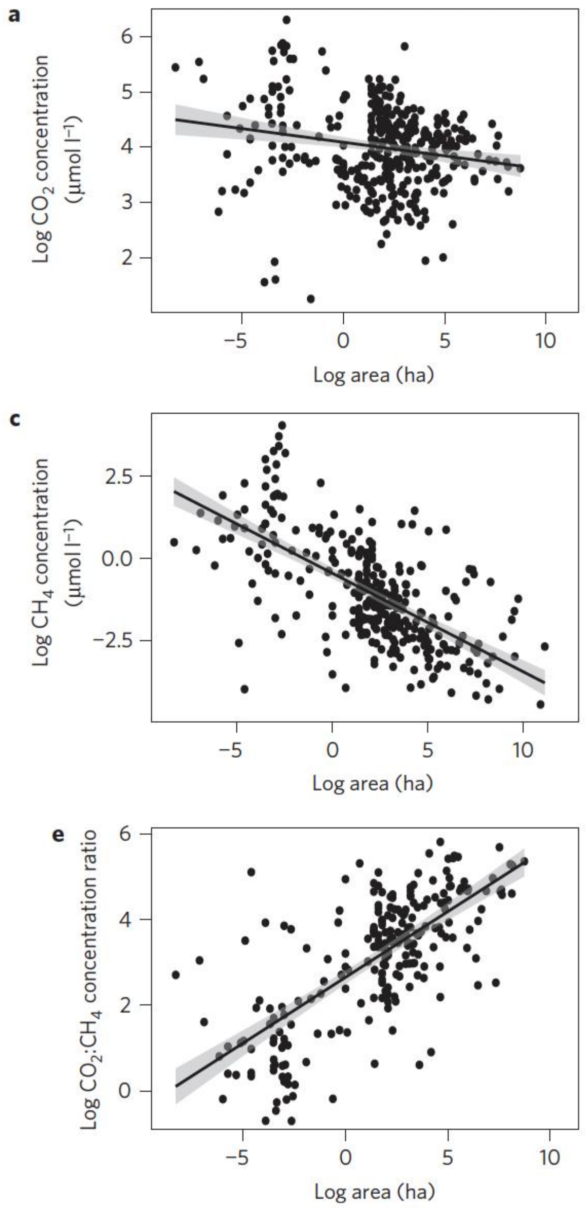
EPFL

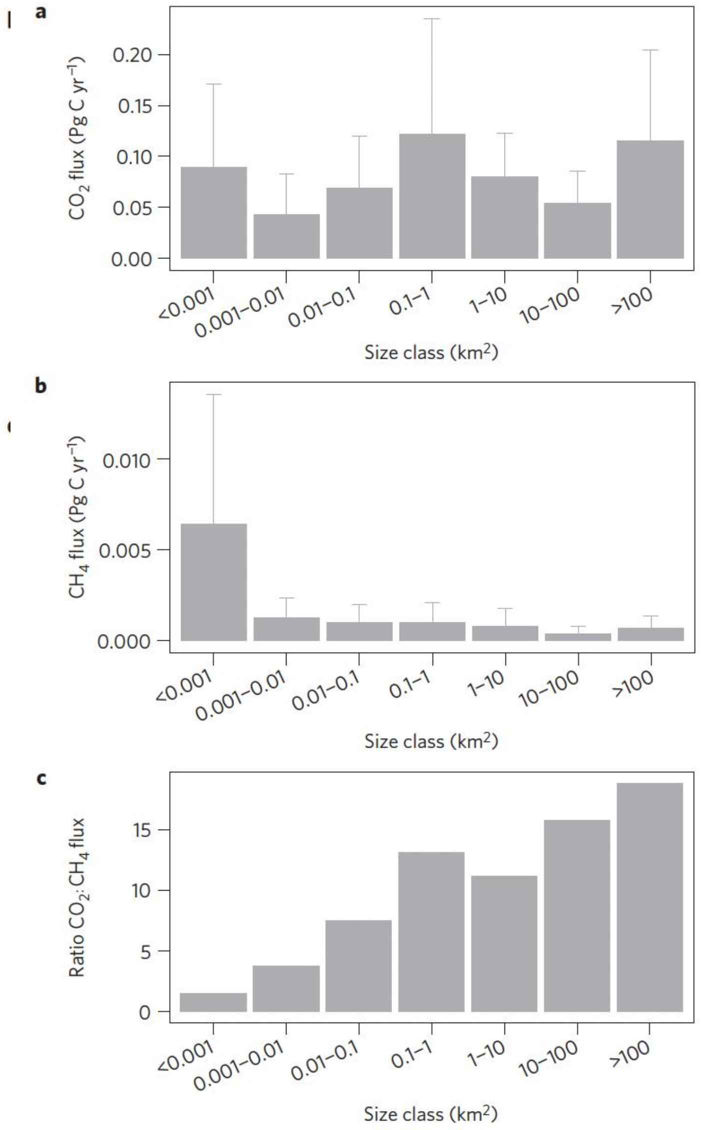
# Ecosystem size matters for GHG emissions

LETTERS
PUBLISHED ONLINE: 1 FEBRUARY 2016 | DOI: 10.1038/NGEO2654
nature geoscience

## Large contribution to inland water $CO_2$ and $CH_4$ emissions from very small ponds

Meredith A. Holgerson* and Peter A. Raymond




- Small ponds emit more $CH_4$ than large ponds - also relative to $CO_2$ emissions
- Large receivers of organic matter and nutrients from the surroundsing landscape (geometry effect)
- Organic matter burial and decomposition leading to hypoxic sedimentary habitats that promote methanogenesis

# Nitrous oxide ($N_2O$)

nature climate change
LETTERS
https://doi.org/10.1038/s41558-019-0665-8

# Increased global nitrous oxide emissions from streams and rivers in the Anthropocene

Yuanzhi Yao[1], Hanqin Tian[1*], Hao Shi[1], Shufen Pan[1], Rongting Xu[1], Naiqing Pan[1] and Josep G. Canadell[2]

- $N_2O$ emssions from streams and rivers are increasing
- Major contributions from fertilizers (N rich), manure and atmospheric depositions
- Headwaters contribute most to $N_2O$ emissions
- Tightly connected via shallow groundwater to land (with agricultural practices)

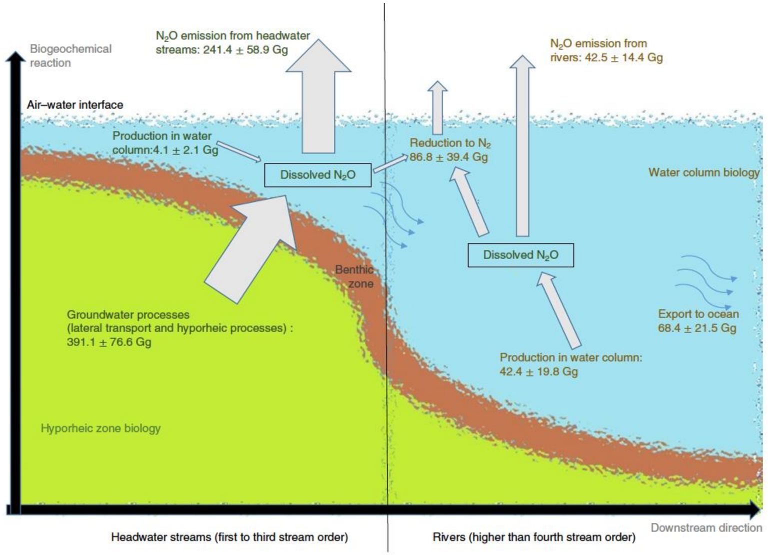



**Fig. 2 | Global annual mean riverine $N_2O$ fluxes during the 2000s estimated by DLEM.** All the arrows denote $N_2O$ fluxes. The left side of the figure depicts biogeochemical processes in the headwater zone simulated in subgrid routine processes at a resolution of 0.5° × 0.5°. The dissolved $N_2O$ of headwater zone exports to downstream river channels (right side) were simulated through the DLEM cell-to-cell routine processes. The benthic zone indicates the sediment surface and its subsurface layers located at the lower end of the waterbodies.

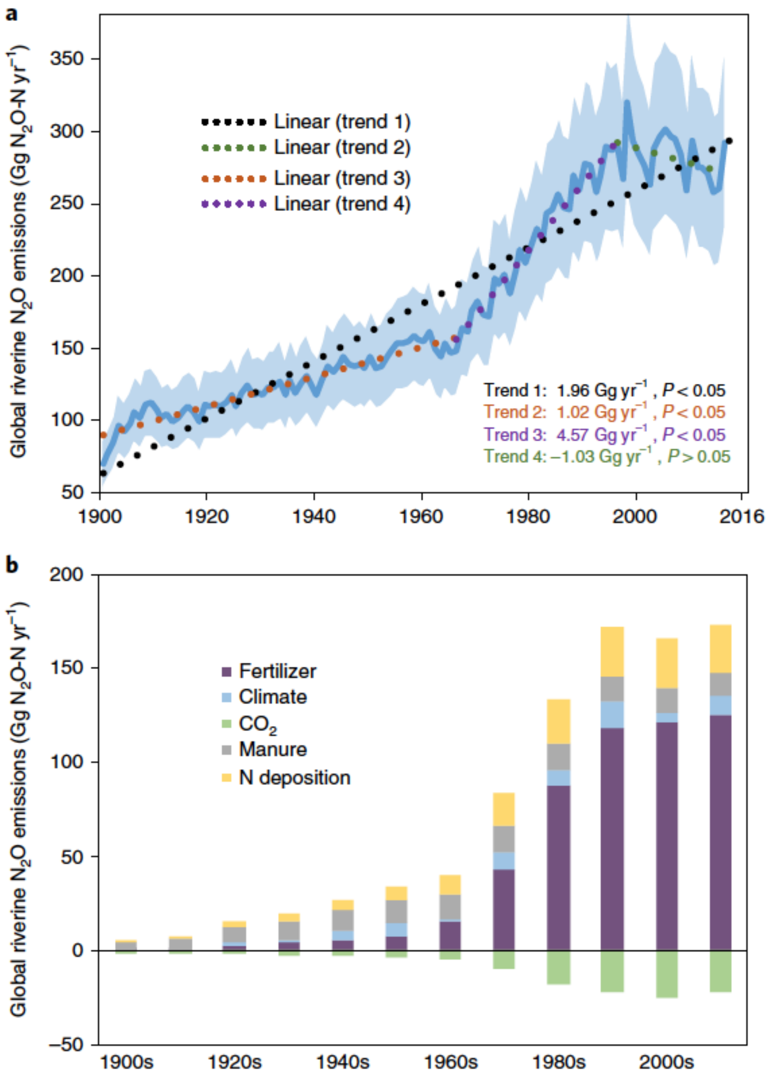



**Fig. 1 | Temporal pattern of global riverine $N_2O$ emission and factorial analysis from 1900 to 2016. a**, Global riverine $N_2O$ emissions from 1900 to 2016 with uncertainty ranges shaded in blue (±1 s.d.). **b**, The factorial contributions to global riverine $N_2O$ emissions from the 1900s to the period 2007–2016.

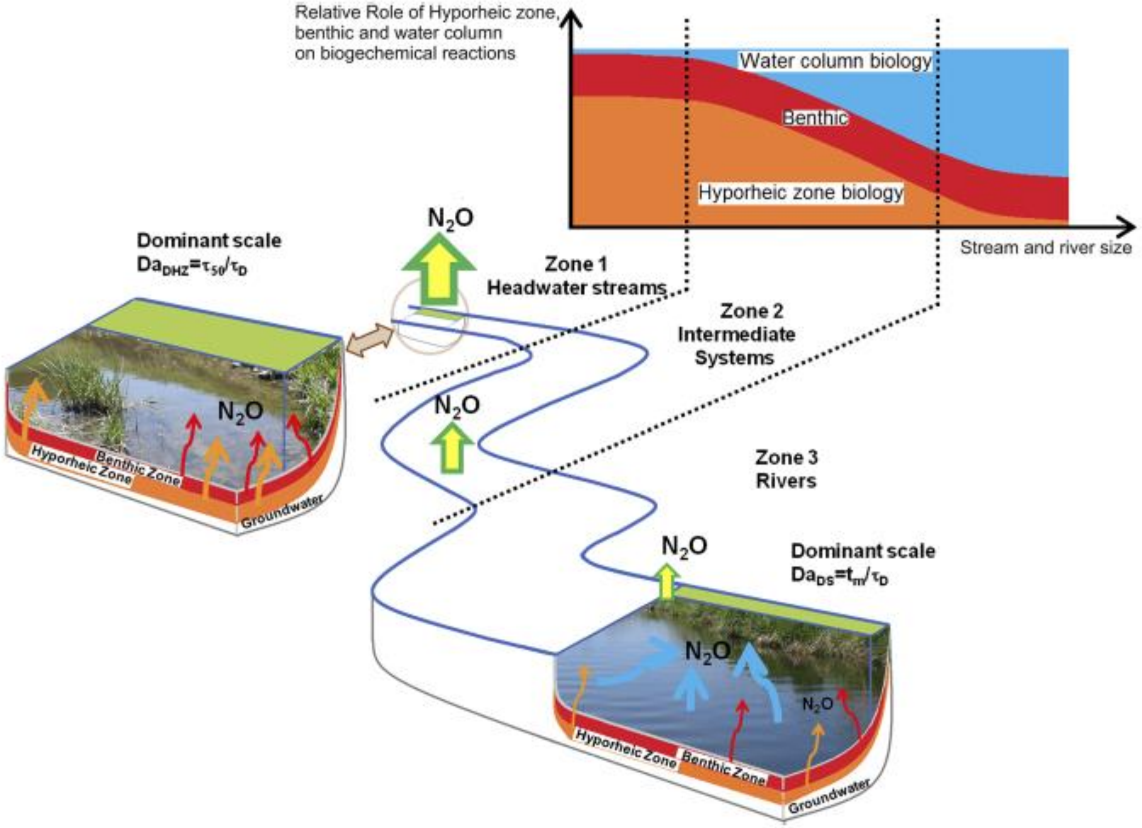
# Role of surface and subsurface processes in scaling $N_2O$ emissions along riverine networks

Alessandra Marzadri[a,1,2], Martha M. Dee[b,1], Daniele Tonina[a,1], Alberto Bellin[c,1], and Jennifer L. Tank[b,1]

Damköhler number for the benthic–hyporheic zone is defined as the ratio between the median hyporheic residence time ($\tau_{50}$), which is an index of the time that streamwater spends within the hyporheic sediment, and the characteristic time of denitrification ($\tau_D$)

The dimension-less flux of $N_2O$, $F_{N2O}$, as the ratio between $F_{N2O}$ and the total flux per unit streambed area of dissolved inorganic nitrogen species [$NO_3$ and $NH_4$] in the stream ($F_{DIN0}$).

The time of turbulent vertical mixing, $\tau_m$, which is the average time for any neutrally buoyant particle to sweep through the water column because of turbulence. Damköhler number for rivers, $Da_{DS} = \tau_m/\tau_D$, with $\tau_m$ replacing $\tau_{50}$ and stating a shift from hyporheic to water column dominated $N_2O$ production.




EPFL

# Role of surface and subsurface processes in scaling $N_2O$ emissions along riverine networks

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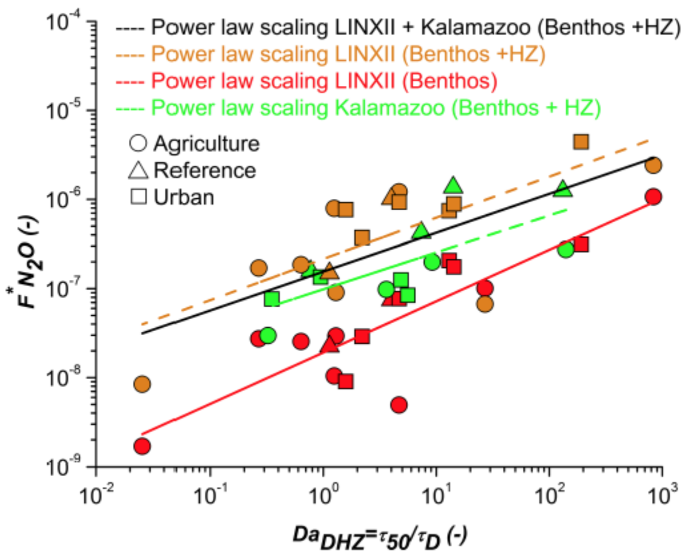



**Fig. 3.** Dimensionless flux of $N_2O$ ($F^*N_2O$) as a function of the denitrification Damköhler number ($Da_{DHZ}$) in the LINXII Study ($n$ = number of streams, $n = 16$) and the Kalamazoo River (Michigan; $n = 12$) streams. $F^*N_2O$ resulting from the production of $N_2O$ within only the benthic zone of the LINXII Study streams is shown with red symbols; the power law regression of these data is shown with the red solid line [$F^*N_2O = 1.91 \times 10^{-8}(Da_{DHZ})^{0.57}$, $r^2 = 0.75$]. Emissions from the benthic–hyporheic zone (combined contribution of both zones, Benthos + HZ) are in orange symbols, and their power regression is shown as the orange dashed line [$F^*N_2O = 2.15 \times 10^{-7}(Da_{DHZ})^{0.46}$, $r^2 = 0.54$]. Emissions from the benthic–hyporheic zone of the Kalamazoo streams scale with $Da_{DHZ}$ [$F^*N_2O = 9.83 \times 10^{-8}(Da_{DHZ})^{0.41}$, $r^2 = 0.54$] as shown by the green line. Because these two relationships (dashed orange and green lines) are not significantly different, we fitted both datasets with a power law [$F^*N_2O = 1.55 \times 10^{-7}(Da_{DHZ})^{0.43}$, $r^2 = 0.48$; black line], which quantifies $N_2O$ emissions from headwaters.

Contents lists available at ScienceDirect
Science of the Total Environment
journal homepage: www.elsevier.com/locate/scitotenv

Global riverine nitrous oxide emissions: The role of small streams and large rivers

Alessandra Marzadri [a,*], Giuseppe Amatulli [b,c,**], Daniele Tonina [d], Alberto Bellin [a], Longzhu Q. Shen [e], George H. Allen [f], Peter A. Raymond [b]

The application of this hybrid modelling approach reveals that small streams (width < 10 m) are the primary sources of riverine $N_2O$ emissions to the atmosphere.

They contribute nearly 36 Gg $N_2O$−N/yr; almost 50% of the entire $N_2O$ emissions from riverine systems (72.8 Gg $N_2O$−N/yr), although they account for only 13% of the total riverine surface area worldwide.

Large rivers (widths >175 m), such as the main stems of the Amazon River (~ 6 Gg $N_2O$−N/yr), the Mississippi River (~ 2 Gg $N_2O$−N/yr), the Congo River (~ 1 Gg $N_2O$−N/yr) and the Yang Tze River (~ 0.7 Gg $N_2O$−N/yr), only contribute 26% of global $N_2O$ emissions, which primarily originate from their water column.

Underscores the role of hyporheic processes in small streams for $N_2O$ production and emissions

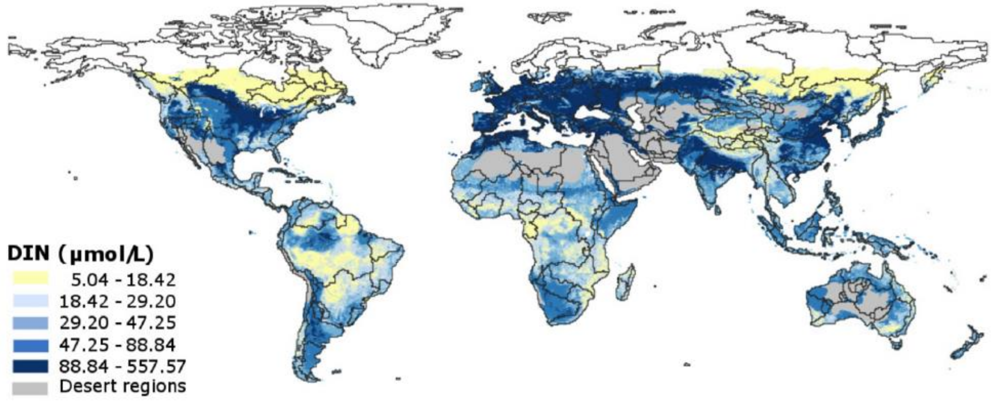



**Fig. 1.** Map of average annual Dissolved Inorganic Nitrogen (DIN) concentration distribution obtained by the data-driven (Random Forest) model (Shen et al., 2020). DIN map obtained as the combination of the in-stream load of ammonium and nitrate DIN = $[NH_4^+] + [NO_3^-]$, (µmol/L).

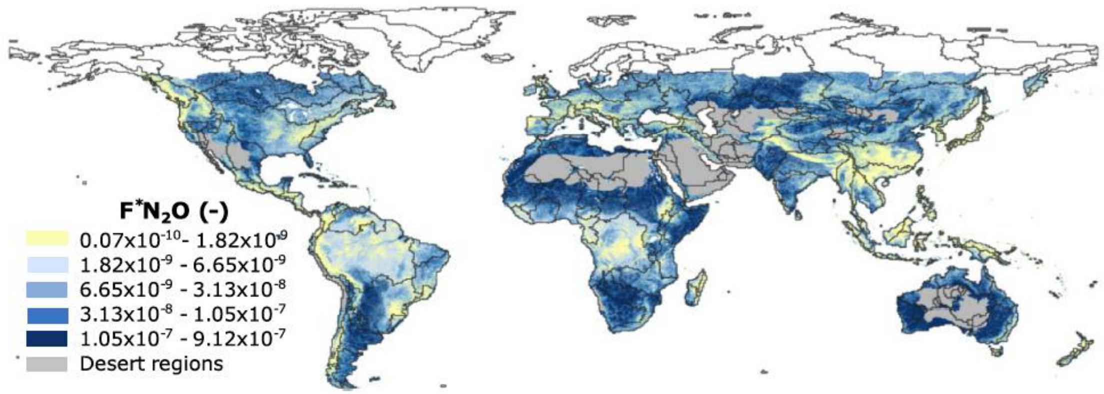



**Fig. 4.** Map of dimensionless $N_2O$ flux ($F^*N_2O$) along the world river network analyzed. Gray areas represent desert regions not accounted in the calculation.

# Stream and river networks

## The multiple dimensions

Vertical

- Connected to the atmosphere through the turbulent surface
- Conencted to the groundwater

Lateral

- Connected to  groundwater, riparian zone and corridor

Longitudinal

- Ample opportunities for downstream processing (see RCC)

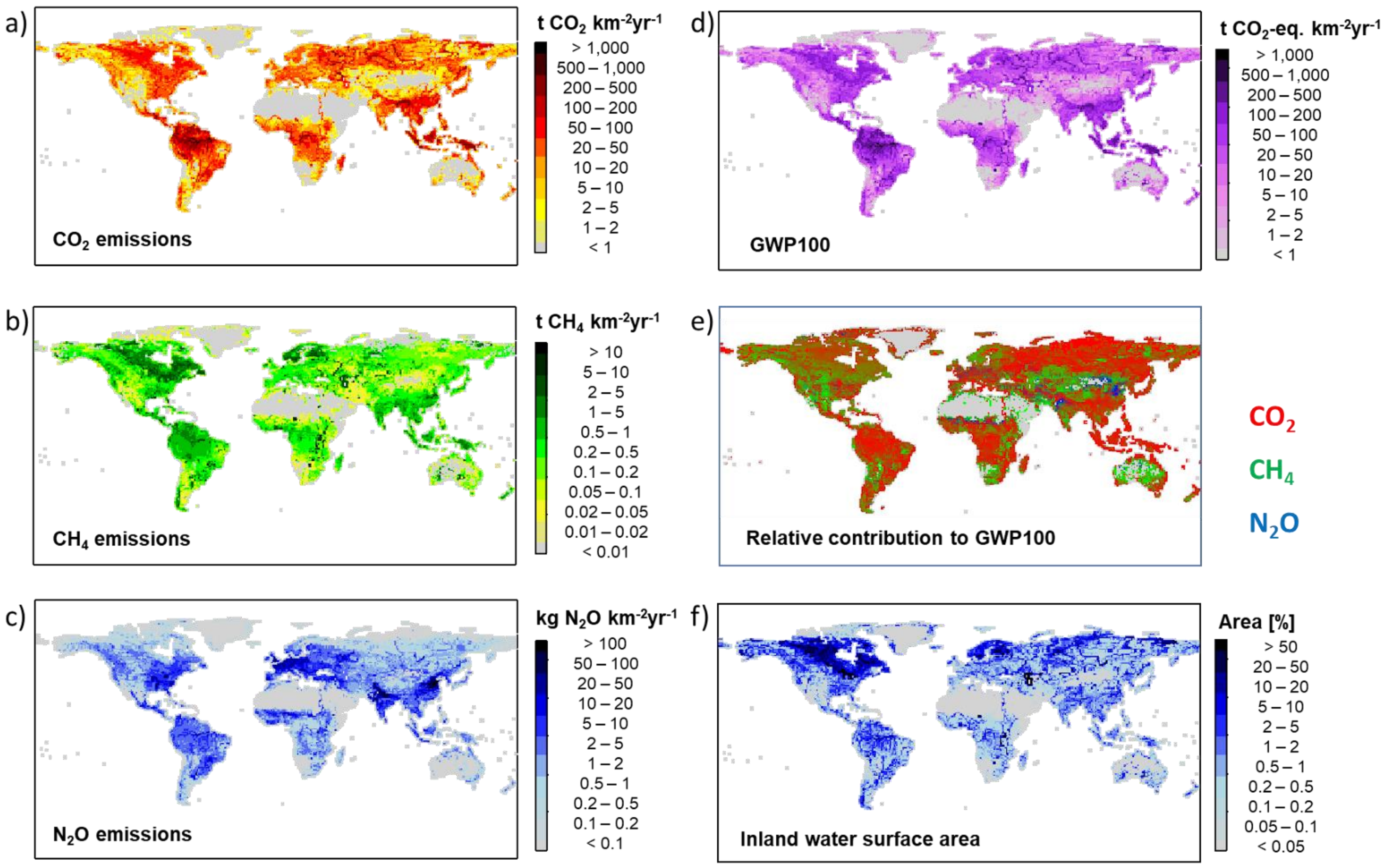
Network

- Small streams are mots abundant and tightly connected to the terrestrial environment

**Makes streams and rivers so important for carbon fluxes despite their minor contribution by alreal extent**

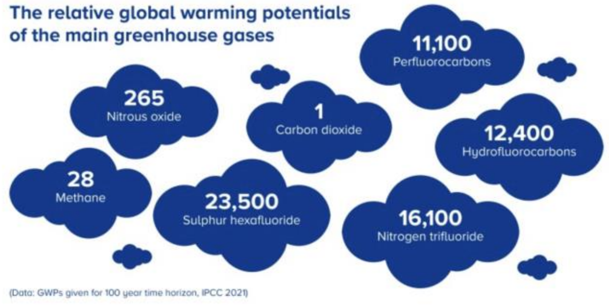
# GHG emissions from inland waters

Global Warming Potential at 100 year horizon
(GWP100)




Lauerwald et al. (in preparation)

- GWP100 of inland water GHG emissions amounts to ~7.6 (4.7-13.0) Pg $CO_2$-eq $yr^{-1}$.
- Roughly three quarters are contributed by net emissions of $CO_2$ the remainder mainly $CH_4$, while contributions of $N_2O$ emissions are nearly negligible.
- Overall streams and rivers emit ca. 80% of inland water GHG




Different GHGs have different global warming potentials

EPFL

# Inland waters and the carbon cycle

Streams, rivers, lakes and ponds are critical components of the global carbon cycle

Tight connection with the terrestrial environment; they receive large terrestrial deliveries of organic matter and $CO_2$ (from weathering and soil respiration)

Important sources of $CO_2$, $CH_4$ and $N_2O$ to the atmosphere (uncertainties are large)

Inland waters are biogeochemical connectors between terrestrial ecosystems, atmosphere and the ocean