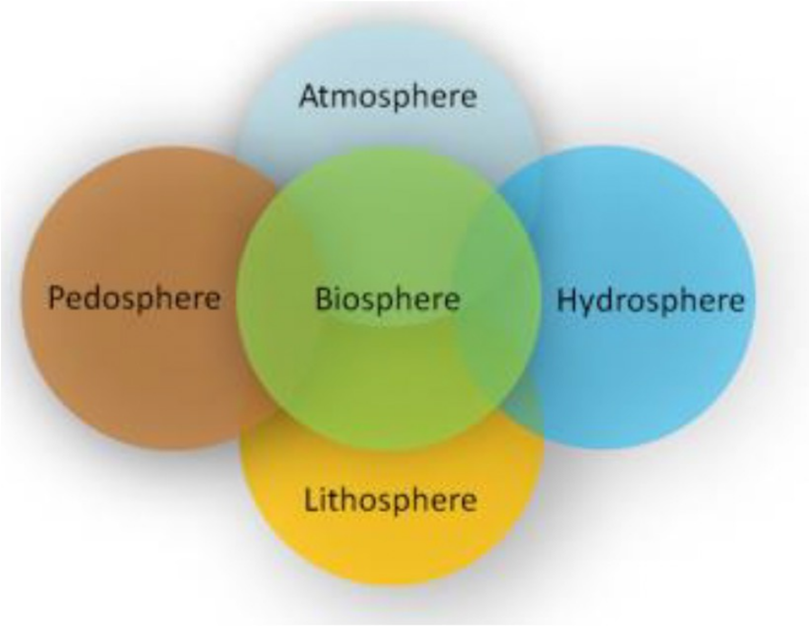
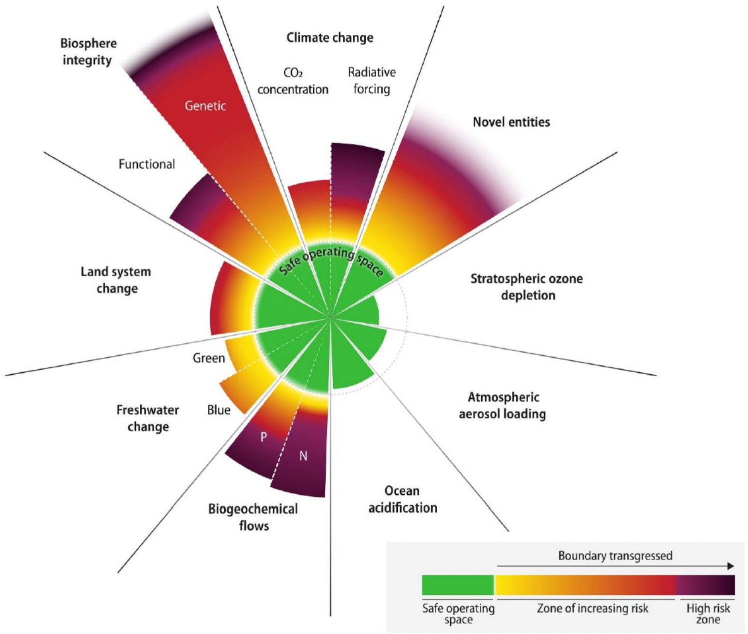
Global change ecology and fluvial ecosystems

Biogeochemistry

EPFL





What is biogeochemistry?

Biogeochemistry is the scientific discipline that explores the interactions between living organisms and the physical and chemical components of the environment.

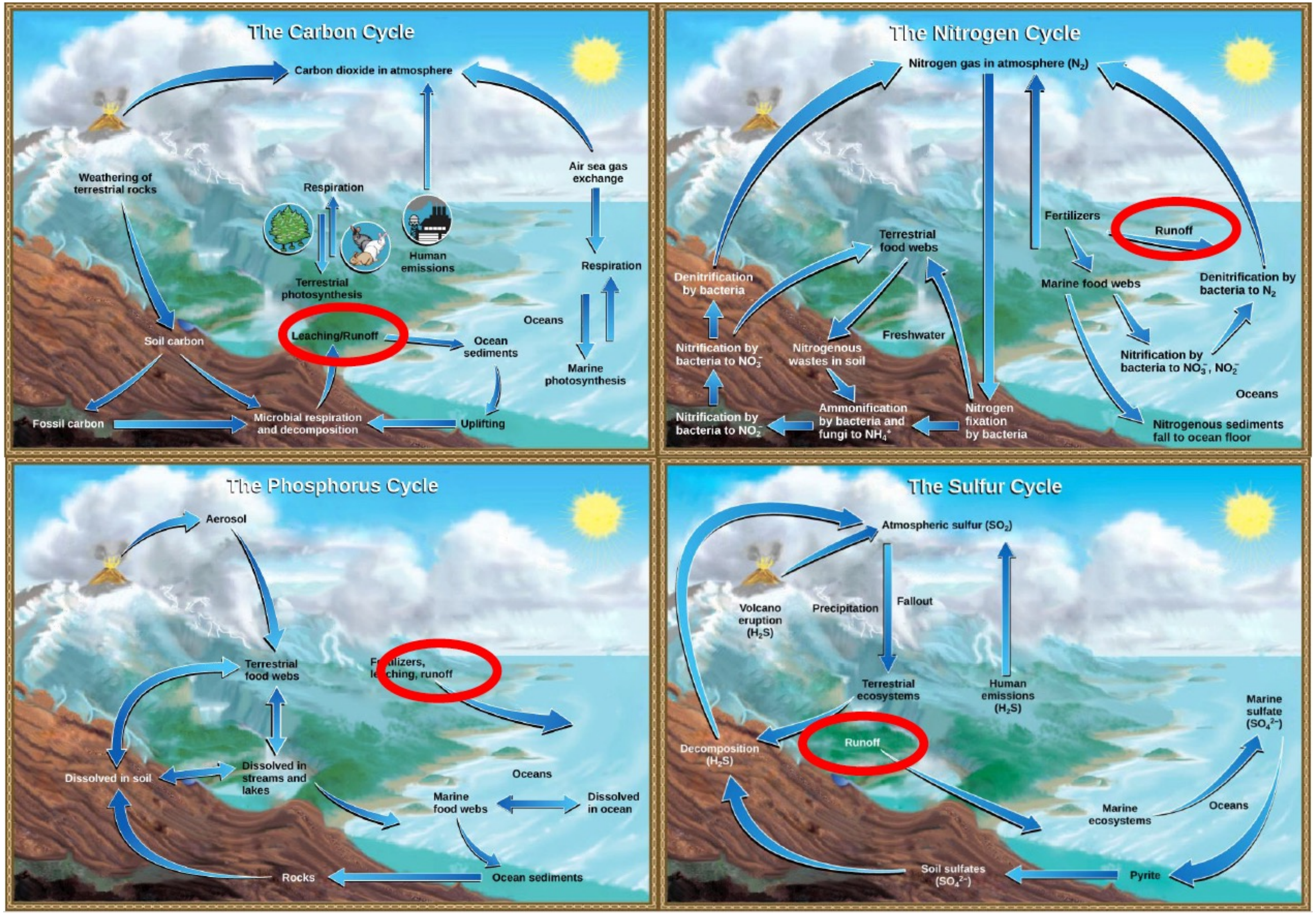
It combines principles from biology, geology, chemistry, and environmental science to study the processes that govern the cycling of elements in ecosystems.

In biogeochemical cycles, elements and compounds move through the atmosphere, hydrosphere, lithosphere, and biosphere in a series of complex processes.

These ecosystem processes include <u>primary production, respiration, decomposition</u>, weathering, erosion, and sedimentation.

Human activities deeply impact biogeochemical cycles – with feedbacks to the climate.

Gobal biogeochemical cycles



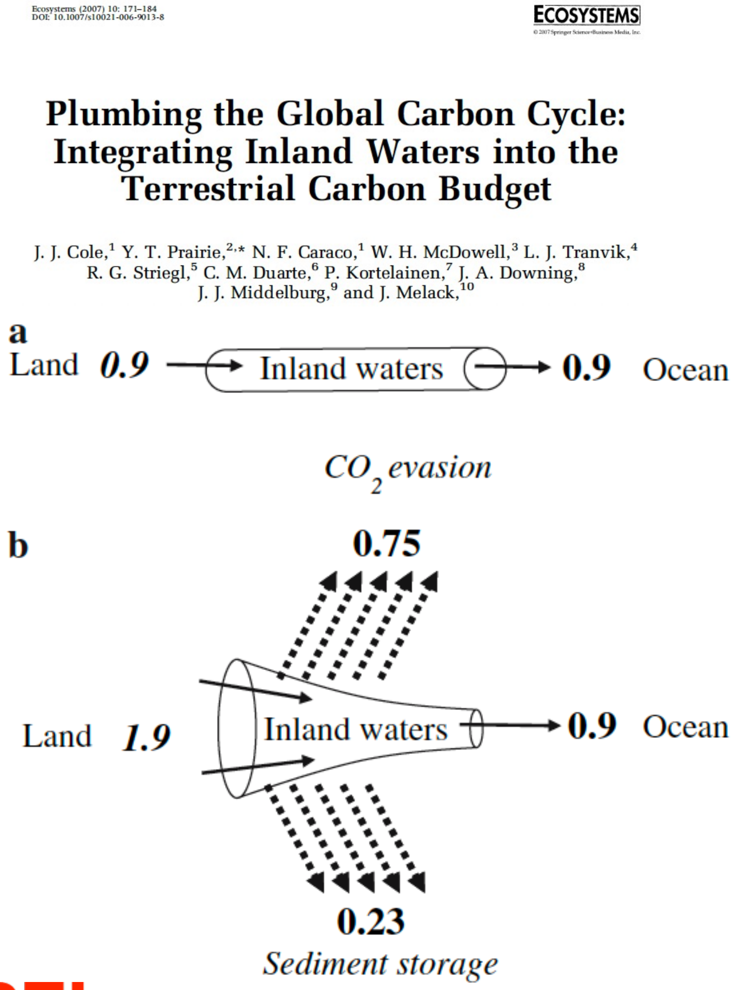
Streams and rivers depicted as pipelines transporting carbon, nitrogen, phosphorus and sulfur from land to the oceans ('runoff')

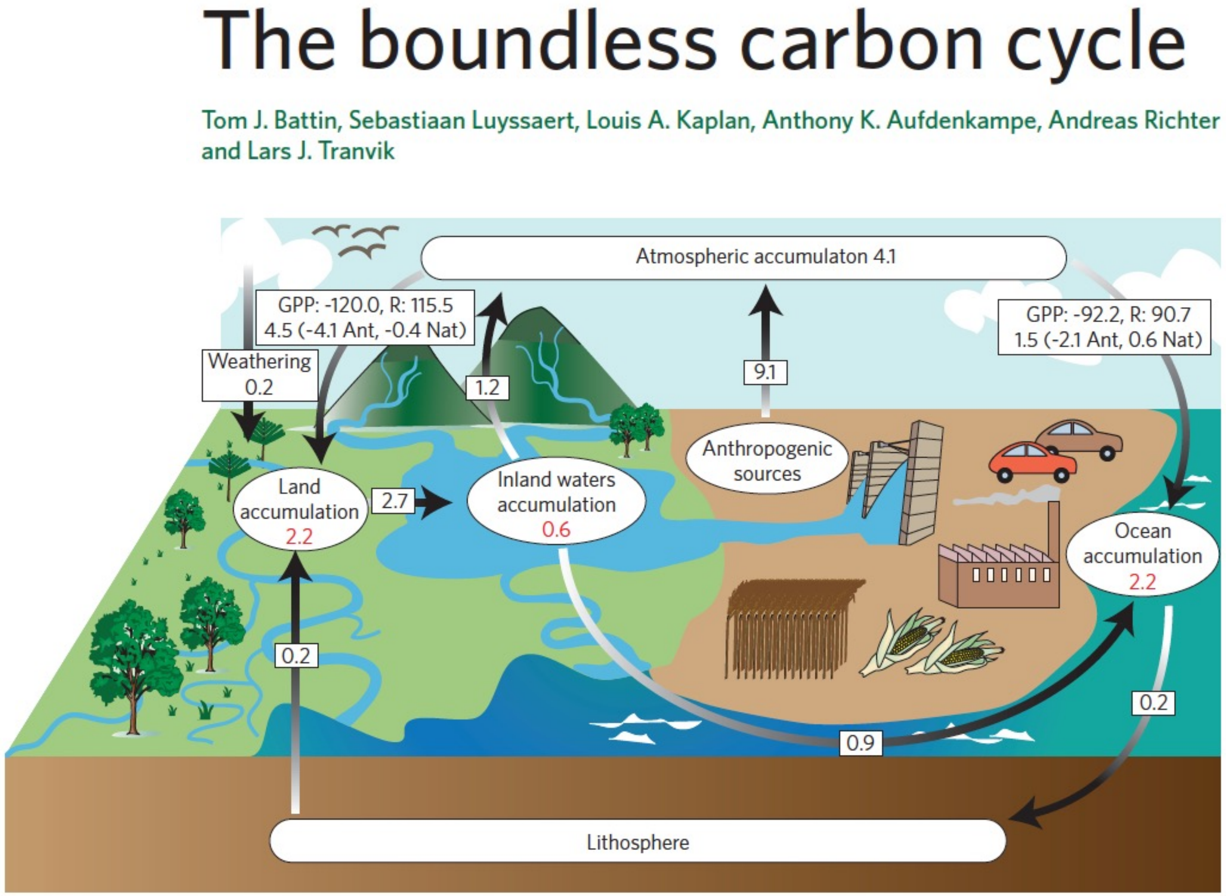
A passive role for fluvial ecosystems

This is wrong!

Streams and rivers are no passive pipes at global scale

- The notion of pipes: hydrology and sediment transport
- ‘Bioreactors’ (see hyporheic flow)



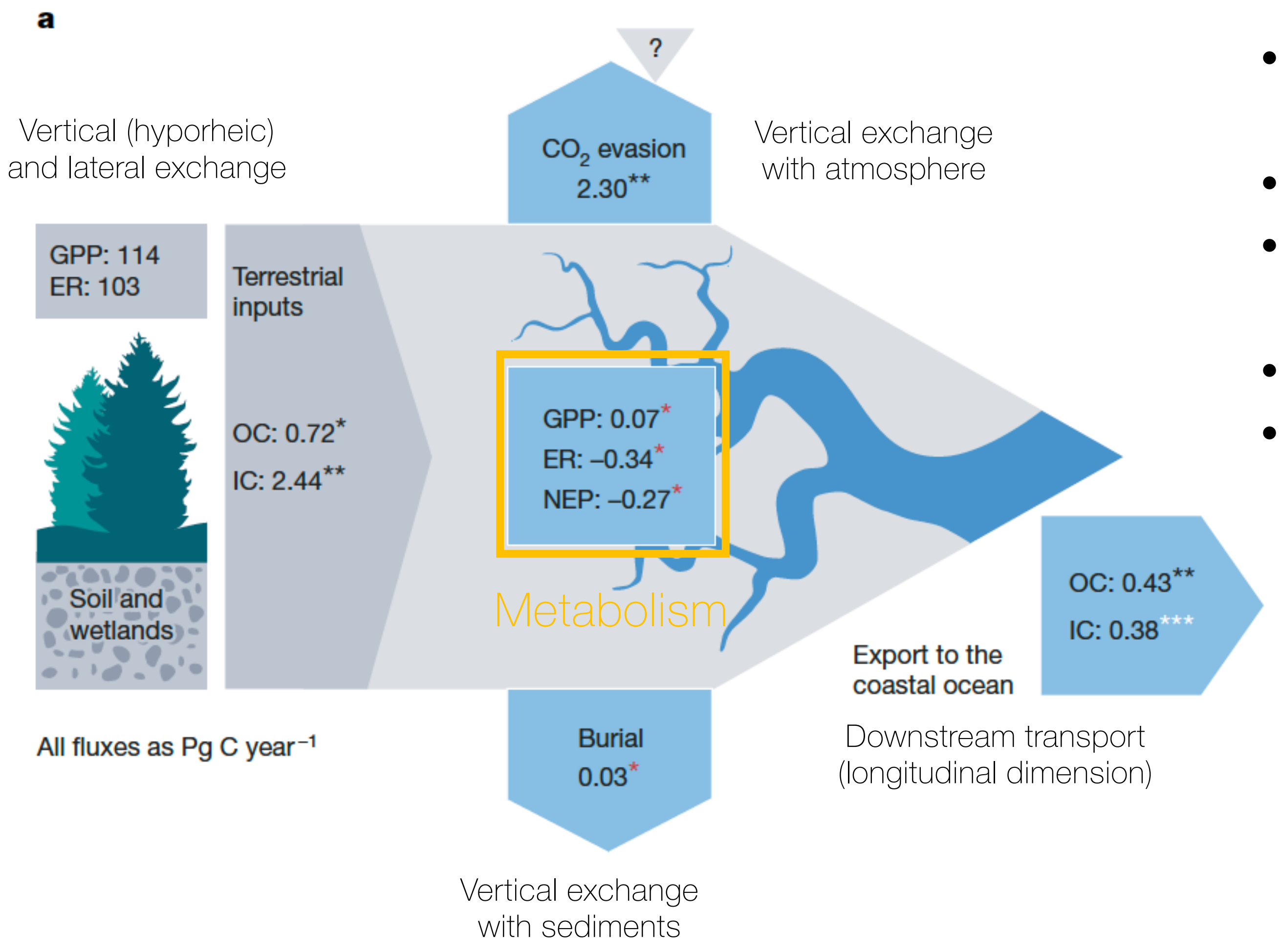


EPFL

Review

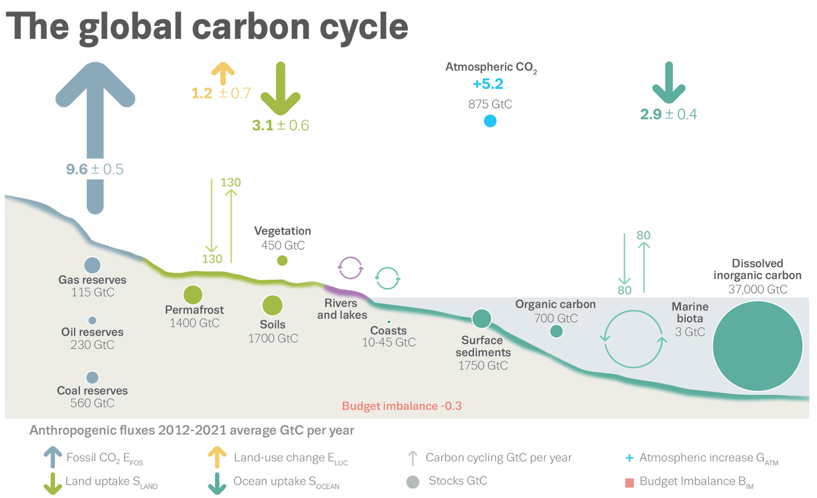
River ecosystem metabolism and carbon biogeochemistry in a changing world

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]



Stream and river networks are the largest biogeochemical nexus between land, ocean and atmosphere

- Fluvial ecosystems receive terrestrial subsidies of organic and inorganic carbon
- Metabolise organic carbon
- Produce and emit CO_2 (and CH_4) to the atmosphere (gas exchange)
- Bury organic carbon (sediments, floodplains)
- Export organic and inorganic carbon to the coastal waters



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

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]

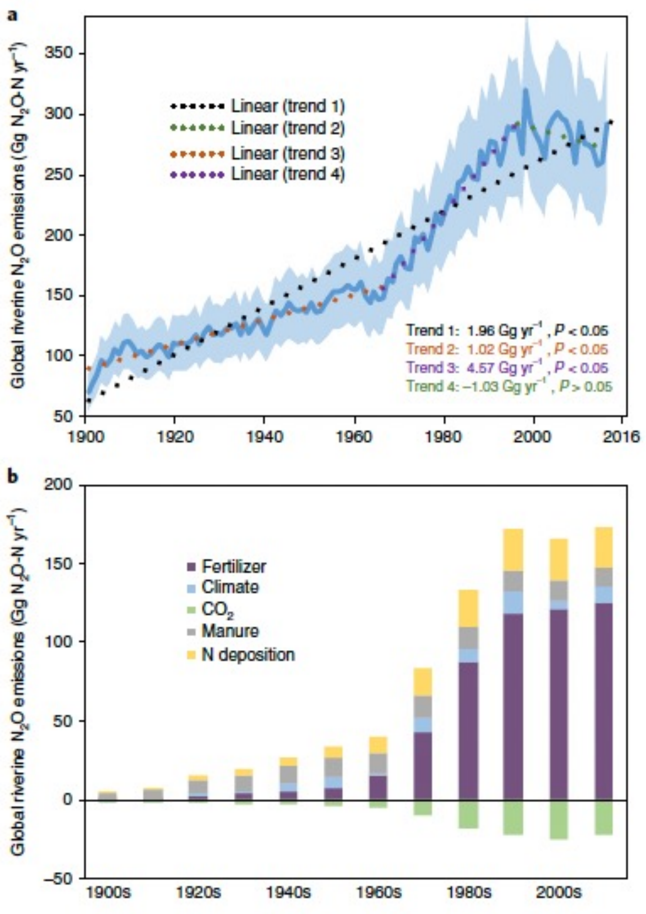
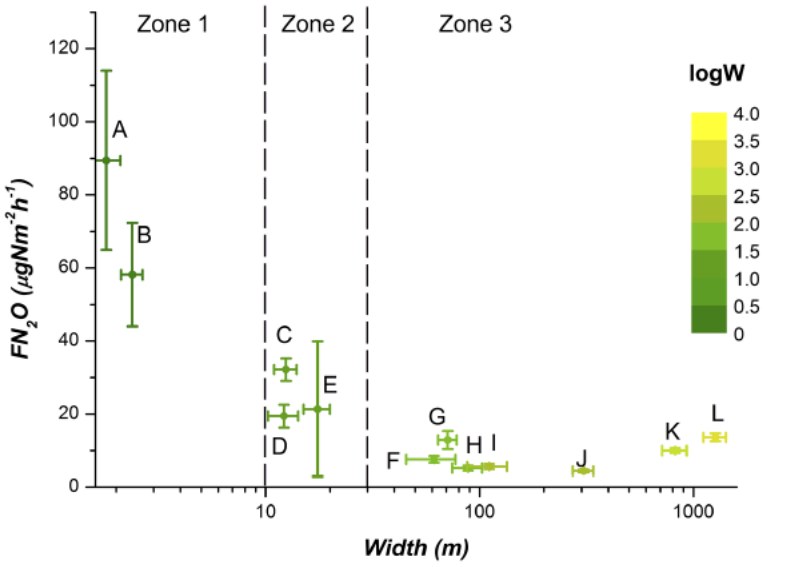


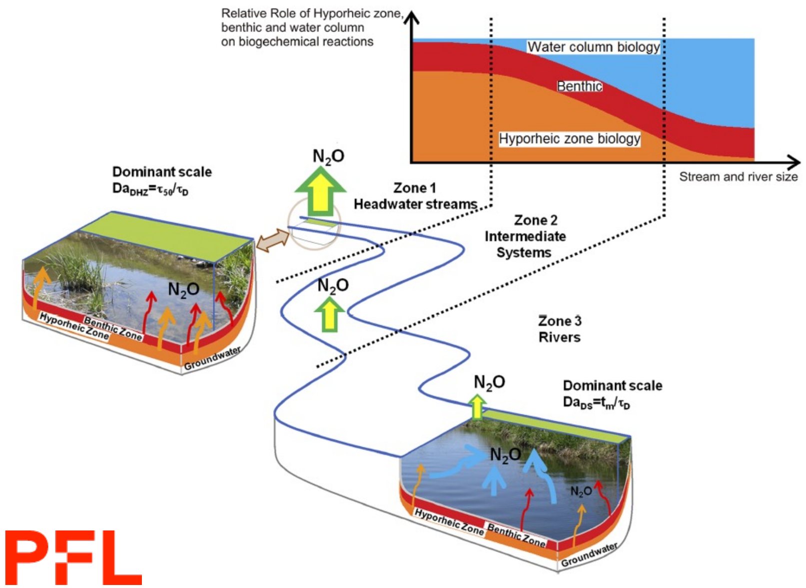
Fig. 1 | Temporal pattern of global riverine N_2O emission and factorial analysis from 1900 to 2016. a, Global riverine N_2O emissions from 1900 to 2016 with uncertainty ranges shaded in blue (±1 s.d.). **b**, The factorial contributions to global riverine N_2O emissions from the 1900s to the period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

- World's streams and rivers are major emittors of N_2O to the atmosphere
- N_2O emissions increasing in time
- Driven by excess N fertilisation and atmospheric deposition

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]





- N_2O evasion fluxes decrease with river width (that is, downstream)
- High surface-to-volume ration upstream, decreasing downstream (that is, water-benthic processes become more important downstream)

- Damköhler number for the benthic–hyporheic zone is defined as the ratio between the median hyporheic residence time (τ_{50}), which is an index of the time that stream water spends within the hyporheic sediment, and the characteristic time of denitrification (τ_D), where $\tau_D = 1/k_D$, with k_D being the denitrification reaction rate
- Dimensionless 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

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

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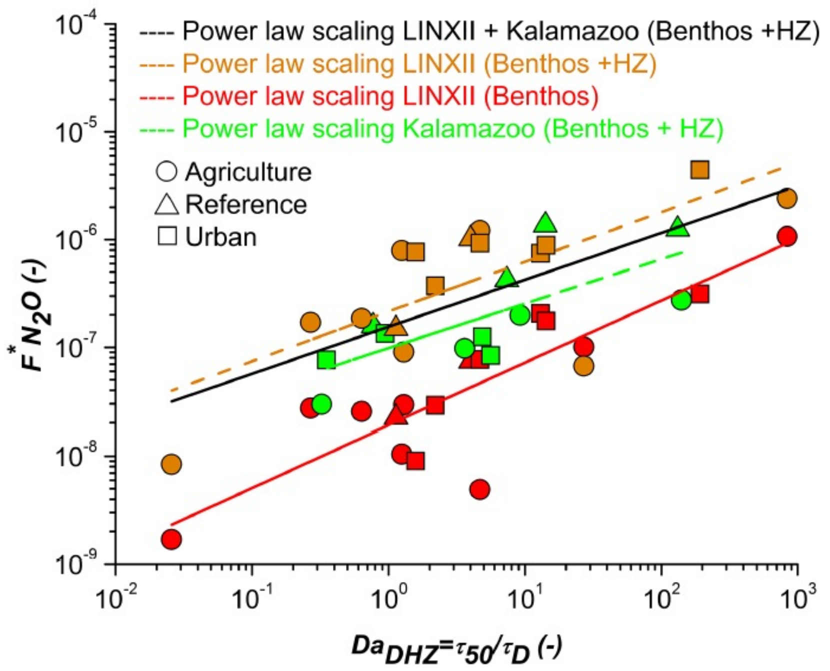


Fig. 3. Dimensionless flux of N_2O (F^*N_2O) as a function of the denitrification Damköhler number (Da_{DHZ}) in the LINXII Study (n = number of streams, $n = 16$) and the Kalamazoo River (Michigan; $n = 12$) streams. F^*N_2O resulting from the production of N_2O within only the benthic zone of the LINXII 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.

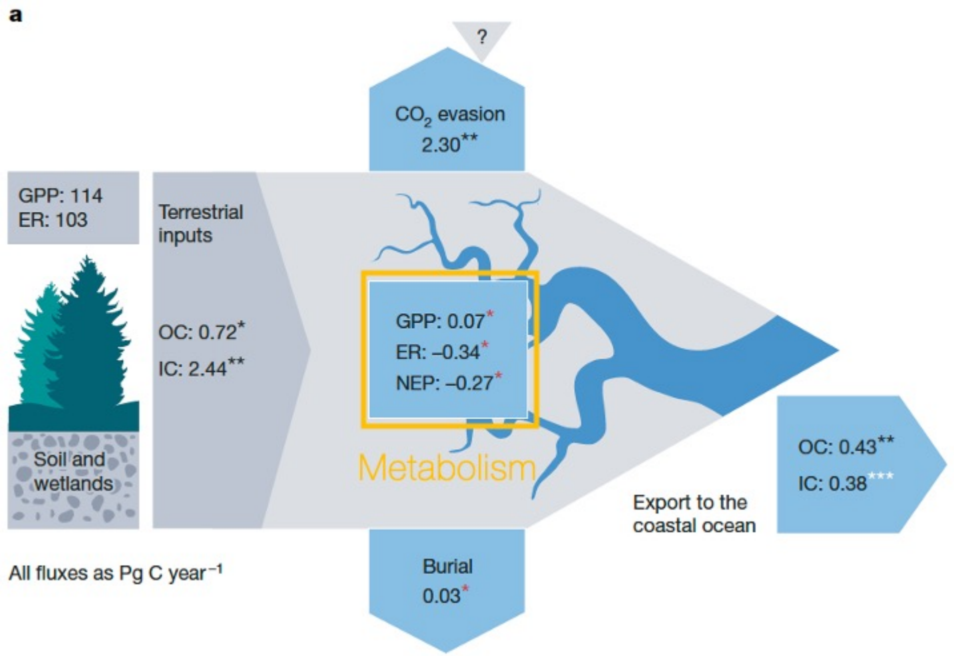
- Dimensionless N_2O emission flux increases with denitrification Damköhler number
- Elevated residence times (relative to characteristic denitrification time) in hyporheic and benthic zones promote denitrification
- Higher denitrification potential when hyporheic and benthic zones are integrated

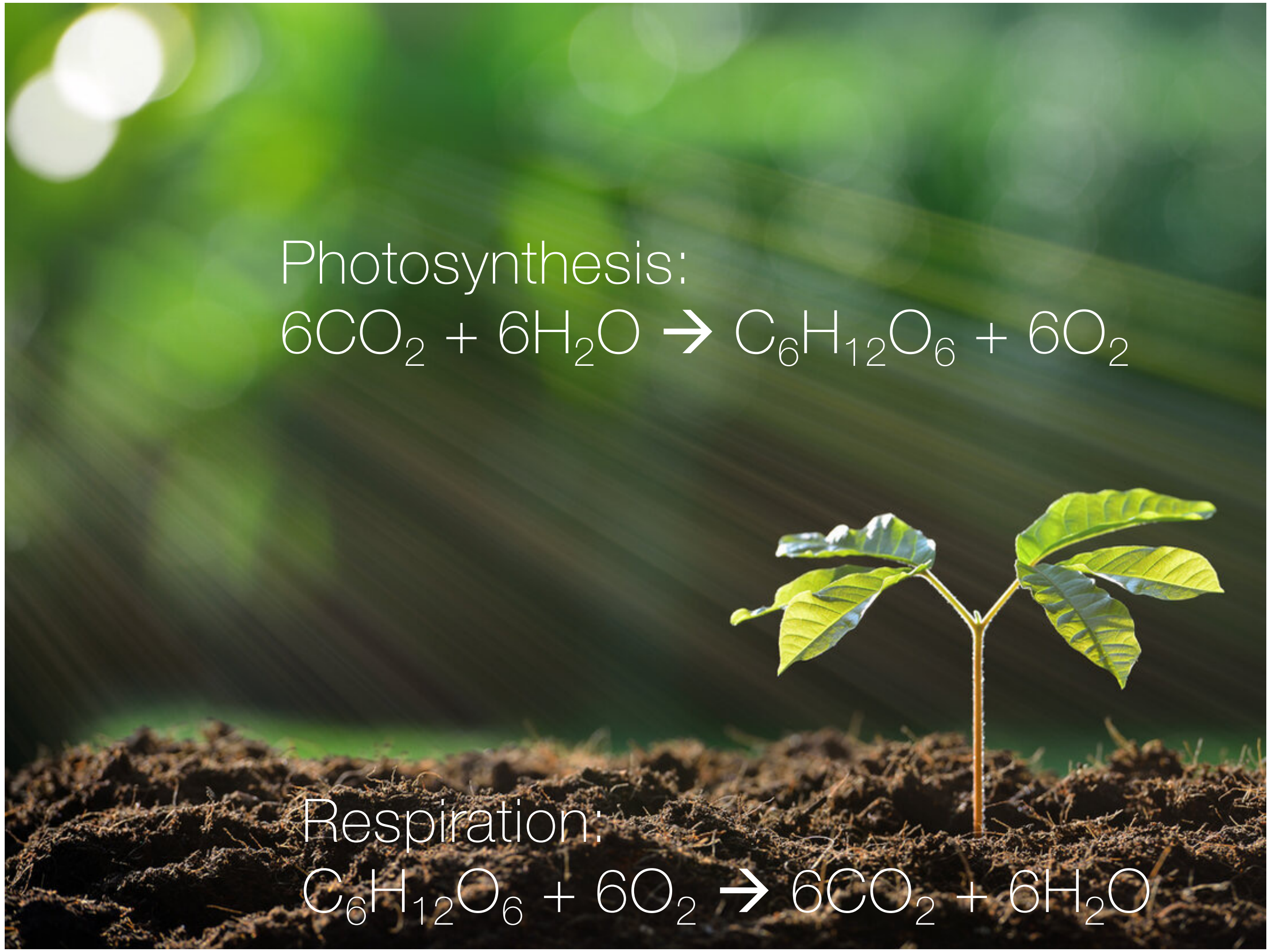
Highlights the role of streambed processes and interaction between streamwater (rich in nitrate and organic carbon) and groundwater (low in oxygen, rich in nitrate)

EPFL

Global streams and rivers do matter for biogeochemical fluxes

What is the engine?





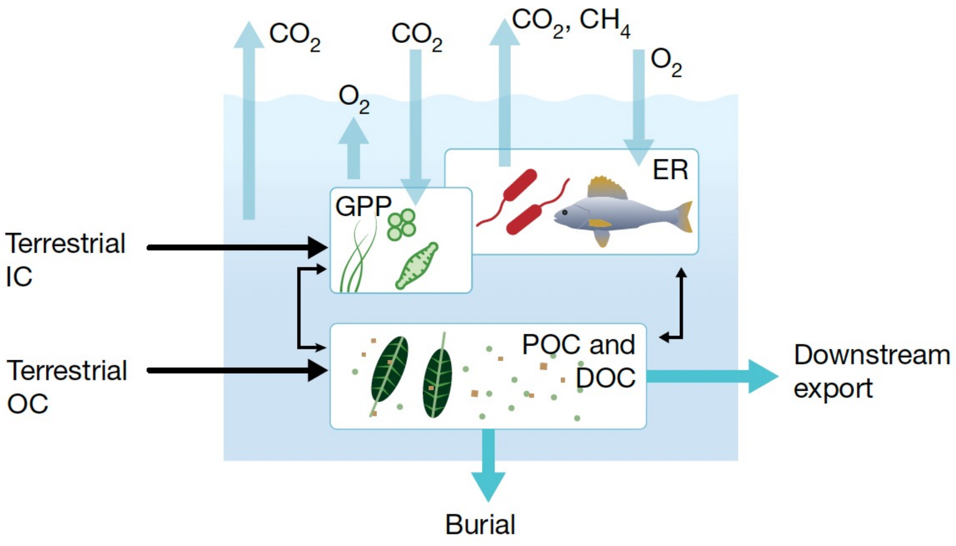
A story of carbon and oxygen

Ecosystem level

Gross Primary Production (GPP)

Ecosystem Respiration (ER)

Net Ecosystem Production (NEP) = GPP-ER



ARTICLE

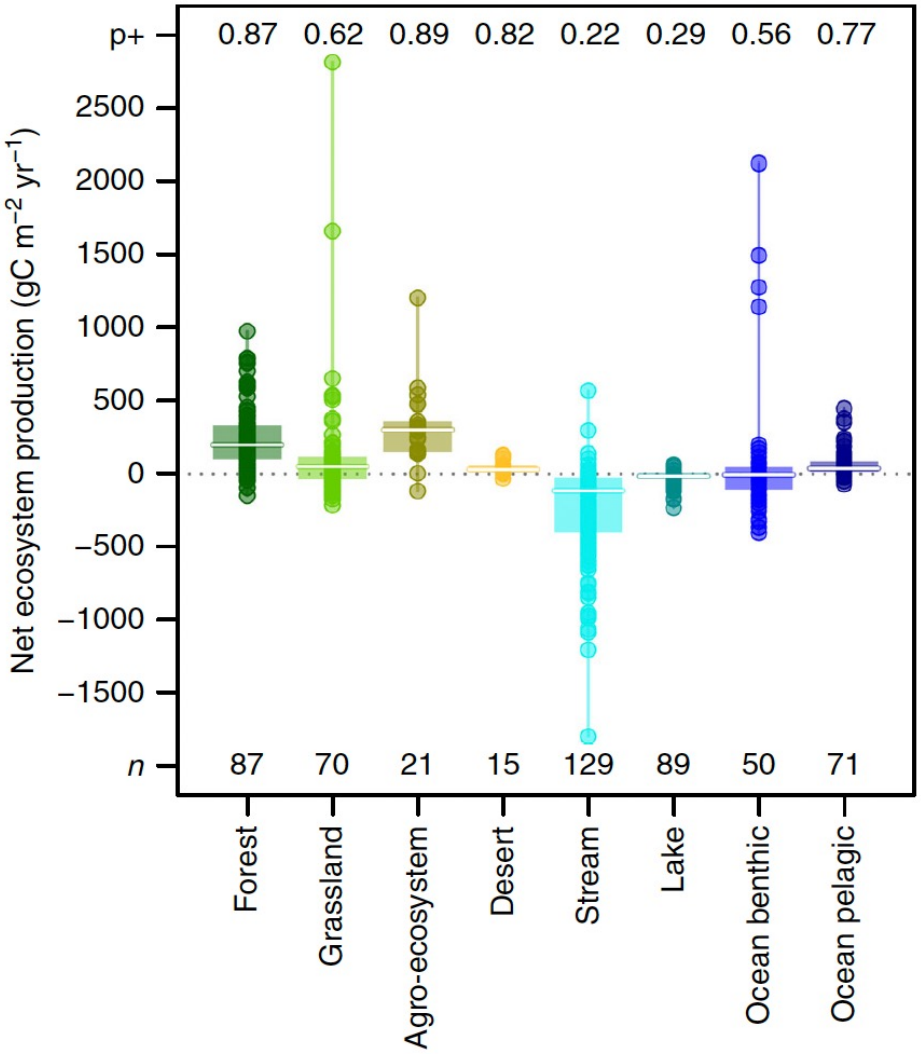
DOI: 10.1038/s41467-018-07238-2 OPEN

Cross-ecosystem carbon flows connecting ecosystems worldwide

Isabelle Gounand[1,2], Chelsea J. Little[1,2], Eric Harvey[1,2,3] & Florian Altermatt[1,2]

Fluvial ecosystems are the most heterotrophic ecosystems

- NEP<0: Heterotrophic; excess energy comes from terrestrial environment
- NEP>0: Autotrophic; excess energy can be exported downstream



EPFL

Light and flow regimes regulate the metabolism of rivers

Emily S. Bernhardt[a,1,2], Phil Savoy[a,b,1], Michael J. Vlah[a], Alison P. Appling[c], Lauren E. Koenig[c,d,e], Robert O. Hall Jr.[e], Maite Arroita[f], Joanna R. Blaszczak[e,g], Alice M. Carter[a,e], Matt Cohen[h], Judson W. Harvey[c], James B. Heffernan[i], Ashley M. Helton[d,j], Jacob D. Hosen[k], Lily Kirk[h], William H. McDowell[l], Emily H. Stanley[m], Charles B. Yackulic[n], and Nancy B. Grimm[o,2]

Fluvial ecosystems are the most heterotrophic ecosystems

- Comparison of annual regimes of terrestrial and river metabolism
- Higher heterotrophy of river ecosystems

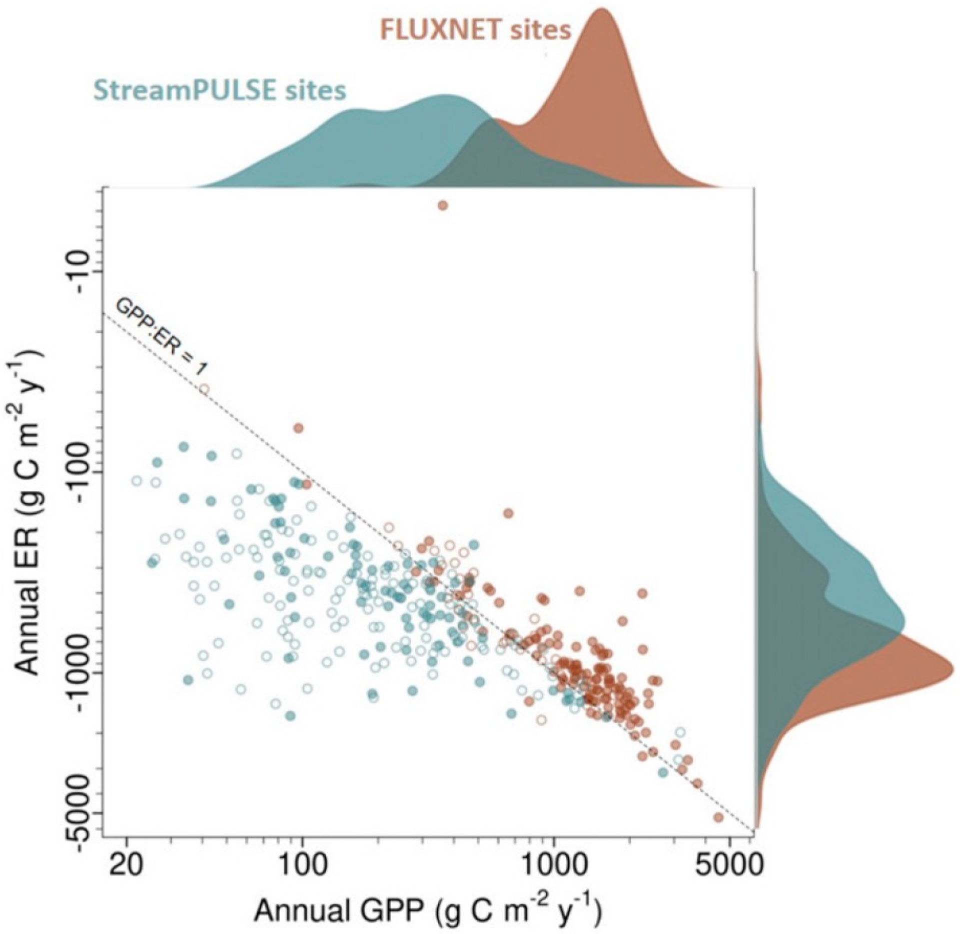


Fig. 1. Annual rates of GPP and ER for 222 river and 162 terrestrial ecosystems are shown as a scatterplot relative to the 1:1 line of balanced aerobic ecosystem carbon production and consumption. The frequency distribution of GPP and ER values within each dataset is shown above and to the right of the scatterplot, with values aligned to the corresponding axis. Open circles indicate sites with at least 60% of all days in each year having estimated rates, and solid circles indicate sites with at least 80% of all days in each year having estimated rates. We show average annual values for sites with multiple years.

Limnol. Oceanogr., 58(6), 2013, 2089–2100

doi:10.4319/lo.2013.58.6.2089

Revisiting Odum (1956): A synthesis of aquatic ecosystem metabolism

Timothy J. Hoellein,[1,*] Denise A. Bruesewitz,[2] and David C. Richardson[3]

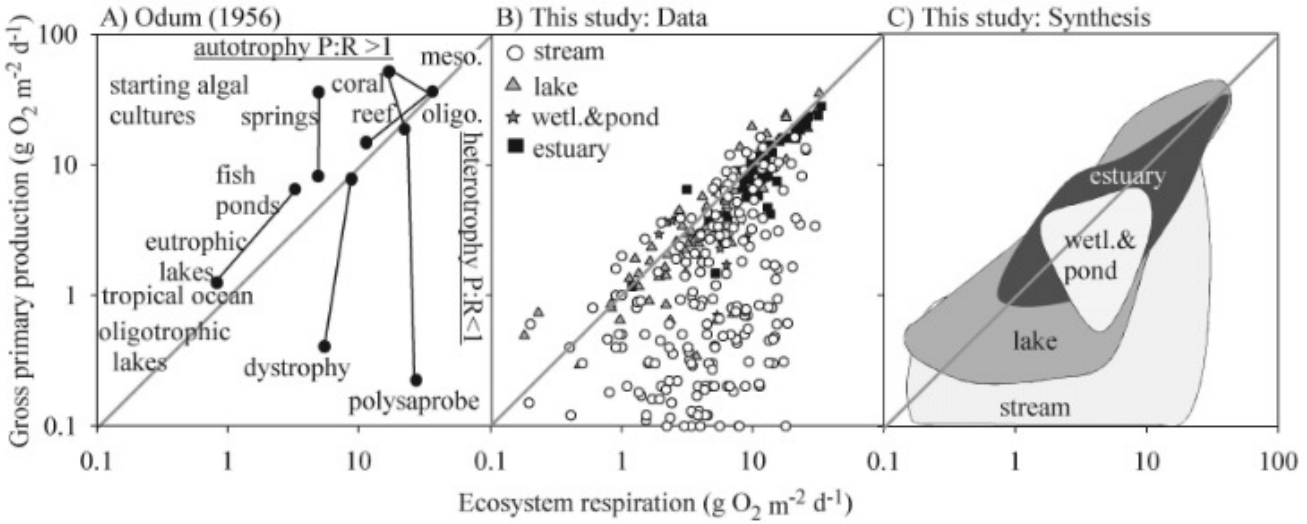


Fig. 1. (A) Odum's (1956) synthesis of metabolism measurements across aquatic ecosystems. Points connected by lines were taken within the same site; meso = mesosaprobe; oligo = oligosaprobe. (B) Our synthesis of data from open-water measurements of metabolism in streams, lakes, wetlands and ponds, and estuaries using identical graphical framework and axes to those in Odum (1956), and (C) a plot of the two-dimensional area that encompasses all data points for each of the four ecosystem types. The gray line indicates 1 : 1 value of GPP : ER on each panel (Odum 1956).

- Streams most heterotrophic among the aquatic ecosystems
- Pronounced hydrological and energetic connectivity with the terrestrial milieu
- Lakes and estuaries have higher GPP and a more balanced ecosystem metabolism

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What are the drivers of fluvial ecosystem metabolism?

Limnol. Oceanogr., 58(6), 2013, 2089–2100

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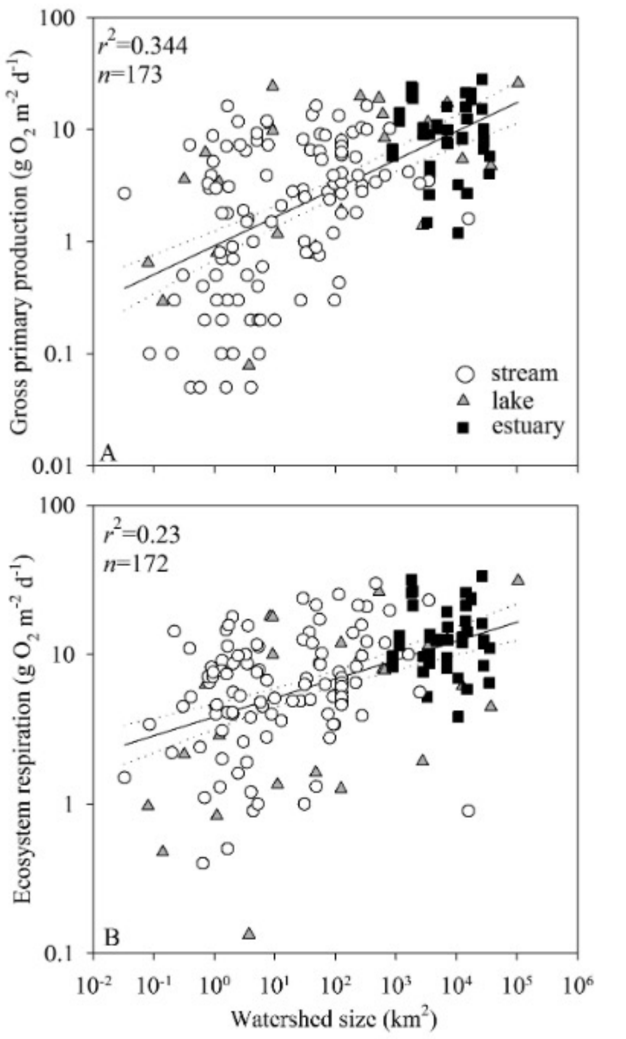
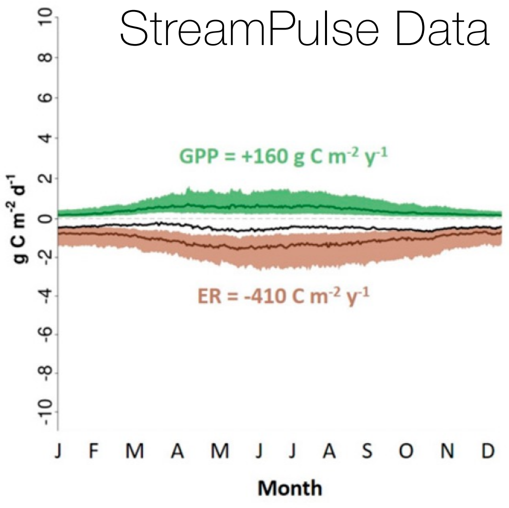


Fig. 3. Simple linear regressions between watershed size and (A) GPP and (B) ER across aquatic ecosystems. The number of replicates and r^2 indicated in each panel are results of significant regressions ($p < 0.001$ in both cases). Dotted lines represent 95% confidence intervals.

- GPP and ER increase with catchment size
- Larger drainage area from where nutrients (N, P) and organic carbon can be mobilized

Light and flow regimes regulate the metabolism of rivers

Emily S. Bernhardt[a,1,2], Phil Savoy[a,b,1], Michael J. Vlah[a], Alison P. Appling[c], Lauren E. Koenig[c,d,e], Robert O. Hall Jr.[e], Maite Arroita[f], Joanna R. Blaszczak[e,g], Alice M. Carter[a,e], Matt Cohen[h], Judson W. Harvey[c], James B. Heffernan[i], Ashley M. Helton[d,j], Jacob D. Hosen[k], Lily Kirk[h], William H. McDowell[l], Emily H. Stanley[m], Charles B. Yackulic[n], and Nancy B. Grimm[o,2]



- Catchment ('watershed') area affects channel width
- Wider channels receive more PAR per unit surface area
- PAR stimulates GPP
- Higher GPP sustains higher ER

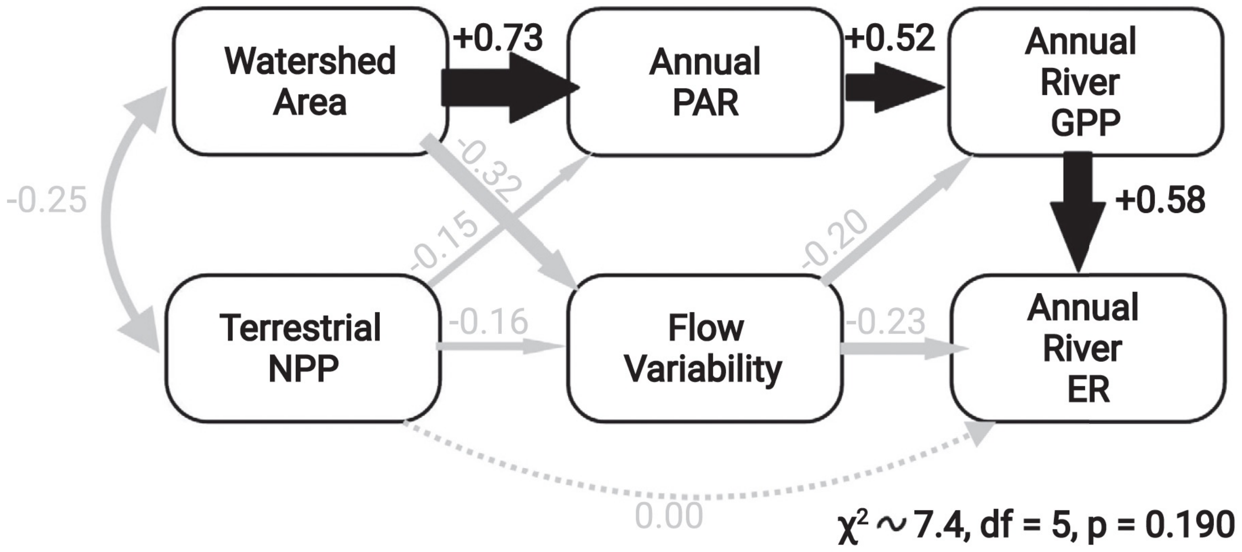


Fig. 3. Structural equation model linking the watershed attributes (area, terrestrial NPP) and stream climate drivers (incoming photosynthetically active radiation [PAR] and flow variability) to GPP and ER across 222 rivers. The final model explained 35% of the variation in GPP and 47% of the variation in ER across sites. In this depiction, the size of the arrows is scaled to the standardized coefficients written alongside each arrow. Solid lines indicate statistically significant effects, while dashed lines indicate a hypothesized effect that was included in the initial model but for which there was no statistical support.

Review

River ecosystem metabolism and carbon biogeochemistry in a changing world

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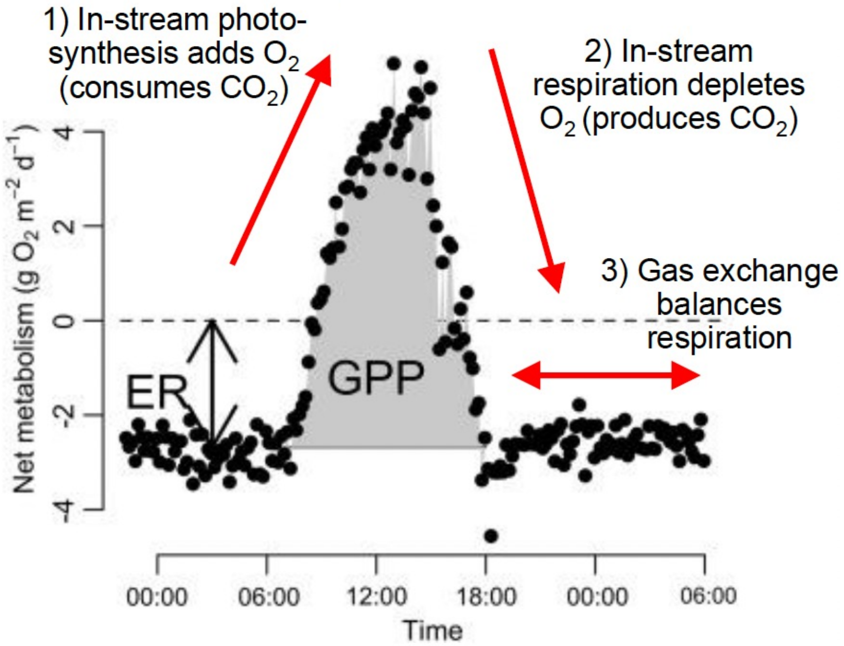

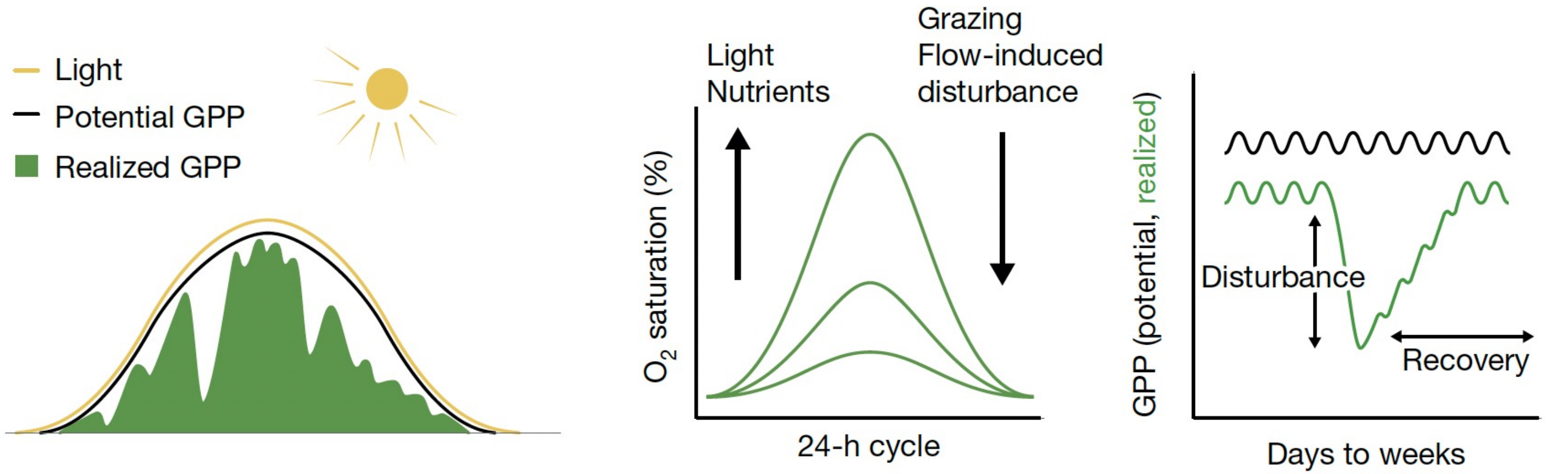

- Light availability (potential versus realized GPP)
- Nutrients (N, P; bottom-up control) and grazing (top-down control)
- Physical disturbance (bed scouring flow events)

EPFL

Light and flow regimes regulate the metabolism of rivers

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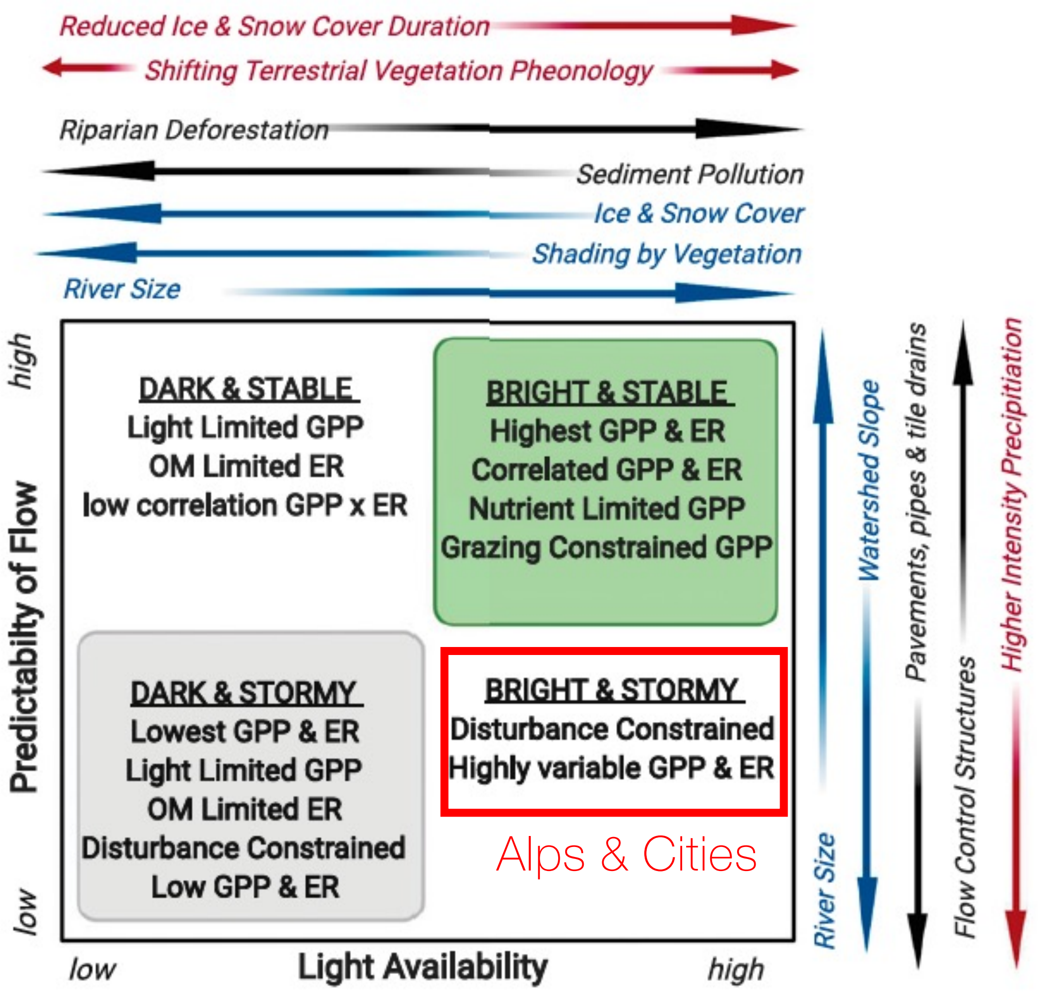
Conceptual understanding of ecosystem metabolism in rivers where productivity is often limited by light and constrained by physical disturbance.

- Blue arrows: riparian vegetation, river size, topography
- Read arrows: climate change
- Black arrows: local anthropogenic alterations



Towards annual regimes of ecosystem metabolism
Environmental sensor technology

https://metalp.epfl.ch/

LIMNOLOGY and OCEANOGRAPHY

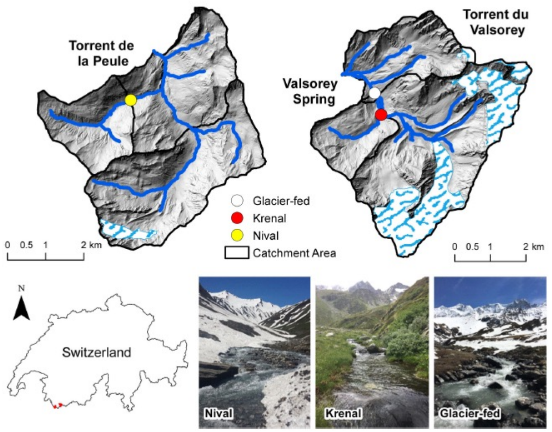
ASLO

Limnol. Oceanogr. 66, 2021, 1594–1610

doi: 10.1002/lno.11670

Daily entropy of dissolved oxygen reveals different energetic regimes and drivers among high-mountain stream types

Marta Boix Canadell,[1] Lluís Gómez-Gener,[1] Mélanie Clémençon,[2] Stuart N. Lane,[2] Tom J. Battin[1*]



Glacier-, snowmelt- and groundwater-fed streams

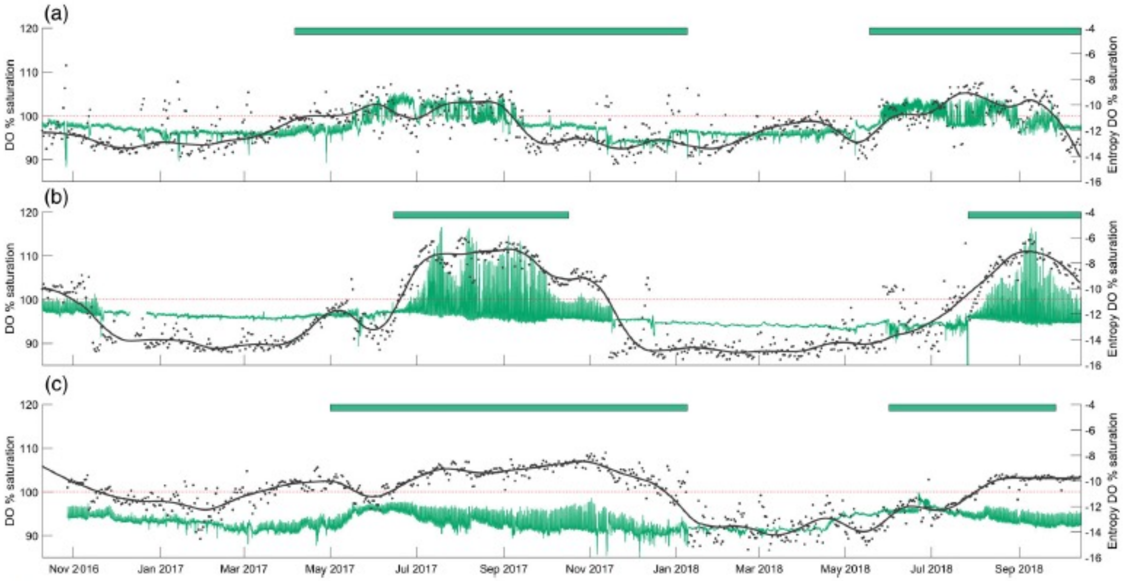


Fig. 3. Time series of dissolved oxygen (DO) % saturation (green) at 10-min frequency, daily entropy DO% saturation (dots) and smoothing filter applied on oxygen entropy data (line; Matlab smooth function: Span = 0.01 and method = rloess). (**A**) Glacier-fed, (**B**) nival, and (**C**) Krenal. Oxygen entropy is natural log transformed for representation purposes. Dashed red line shows 100% saturation limit. See caption Fig. 2 for explanation of the bars above each plot.

- Leveraging oxygen time series to infer annual regimes of stream ecosystem energetics
- Higher value of daily entropy indicates a greater range of diurnal variability of DO saturation as compared to the daily mean value.
- Essentially daily DO entropy informs on the departure of percent DO saturation from its baseline and is thus assumed to reflect biological (e.g., GPP) and physical (e.g., gas exchange) processes.

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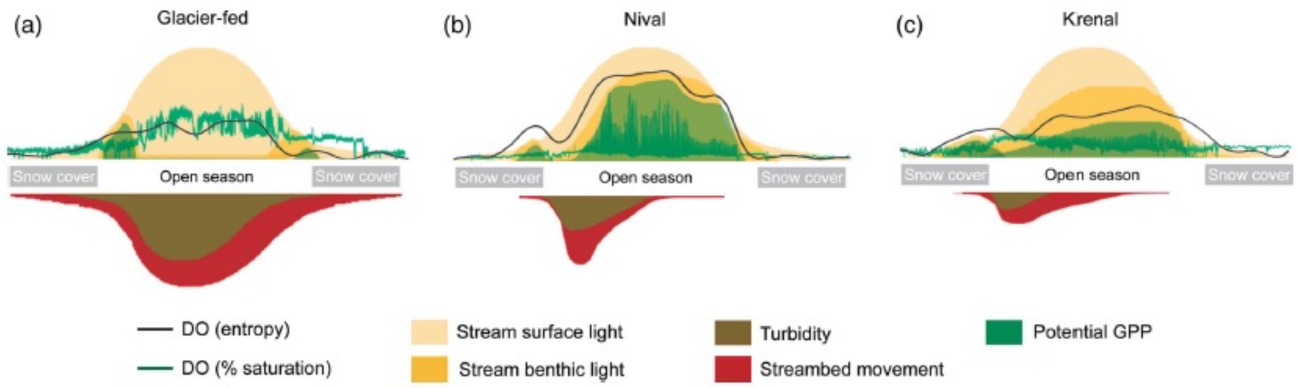


Fig. 6. Conceptual model of three annual energetic regimes for streams with contrasted physical and hydrological regimes typical for high-alpine catchments: a glacier-fed (**A**), a nival (**B**), and a krenal stream (**C**). The measured annual dissolved oxygen (DO) regimes (as both percentage of saturation and entropy) are the green and black lines, respectively. The annual pattern of potential solar radiation (i.e., radiation reaching the stream surface) is shown in light yellow while the actual incident solar radiation (i.e., radiation reaching the streambed bottom) in dark yellow. The annual patterns associated to physical disturbances (i.e., turbidity and streambed movement) are shown in brown and red, respectively. In high-alpine streams, the interplay of both light and disturbance regimes drives the timing, magnitude and extent of productivity periods occurring at annual basis (i.e., maximum potential for gross primary production (GPP)).

- Leveraging oxygen time series to infer annual regimes of stream ecosystem energetics
- Energetic regimes depend on light availability mediated by turbidity (suspended load) and streambed movement (bedload)
- Depending on stream types (i.e., glacier-, snowmelt- or groundwater-fed)
- Look into the future when glacier-fed streams will look more alike as groundwater-fed streams today

Urban streams

LIMNOLOGY and OCEANOGRAPHY

ASLO

Limnol. Oceanogr. 64, 2019, 877–894

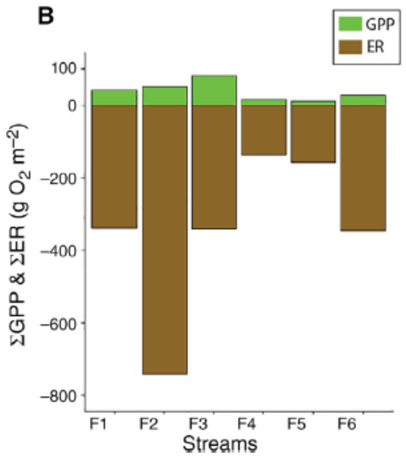
doi: 10.1002/lno.11081

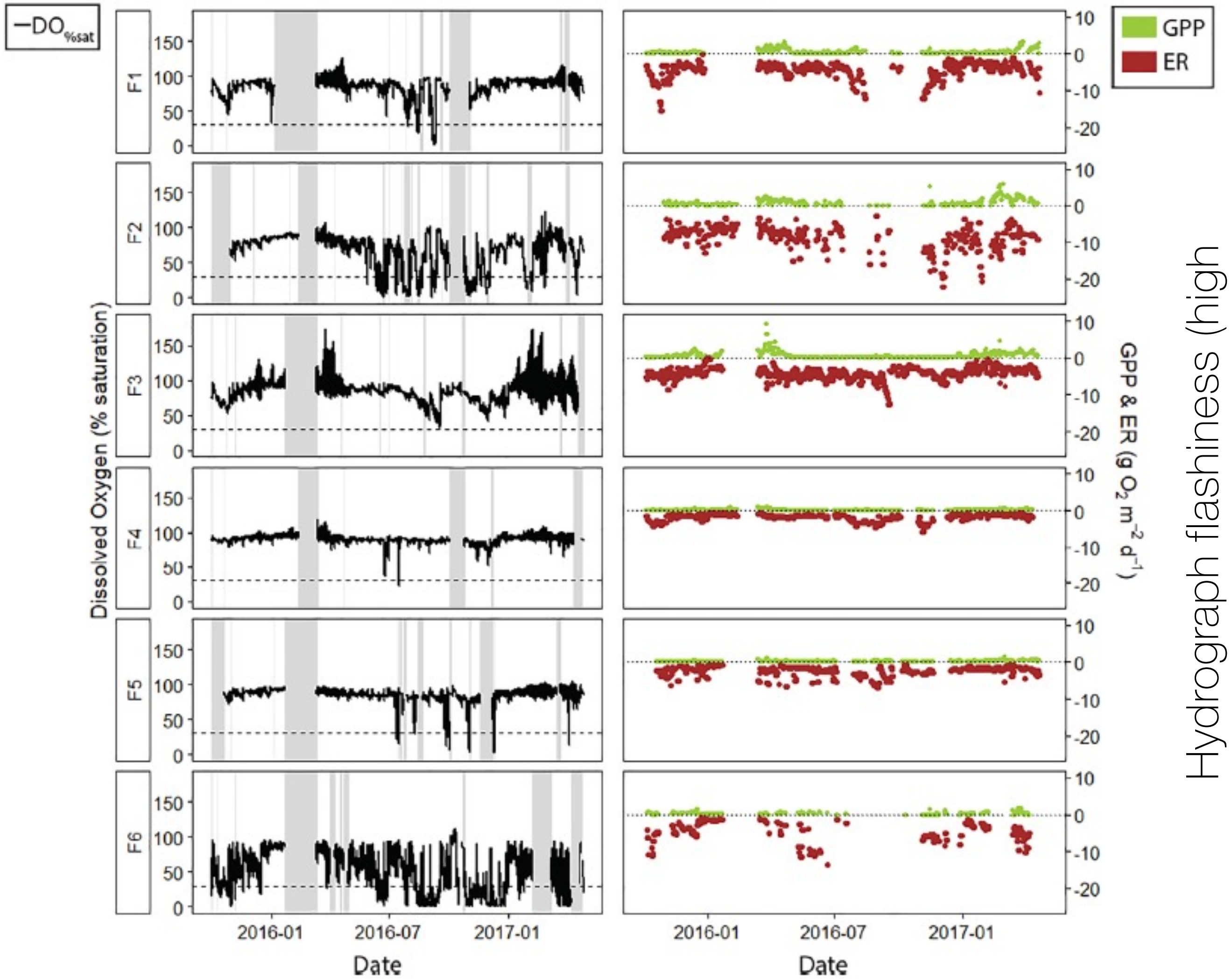
Scoured or suffocated: Urban stream ecosystems oscillate between hydrologic and dissolved oxygen extremes

Joanna R. Blaszczak,*[1,2] Joseph M. Delesantro,[3] Dean L. Urban,[2] Martin W. Doyle,[2] Emily S. Bernhardt[1]

<u>Urban streams</u>: Channelized, little canopy cover, high degree of flashiness, high inputs of organic matter (OM)

- Unpredicted peak-flow events keep GPP low
- ER greatly exceeds GPP – owing to OM inputs





Hydrograph flashiness (high hydrological responsiveness)

LIMNOLOGY and OCEANOGRAPHY

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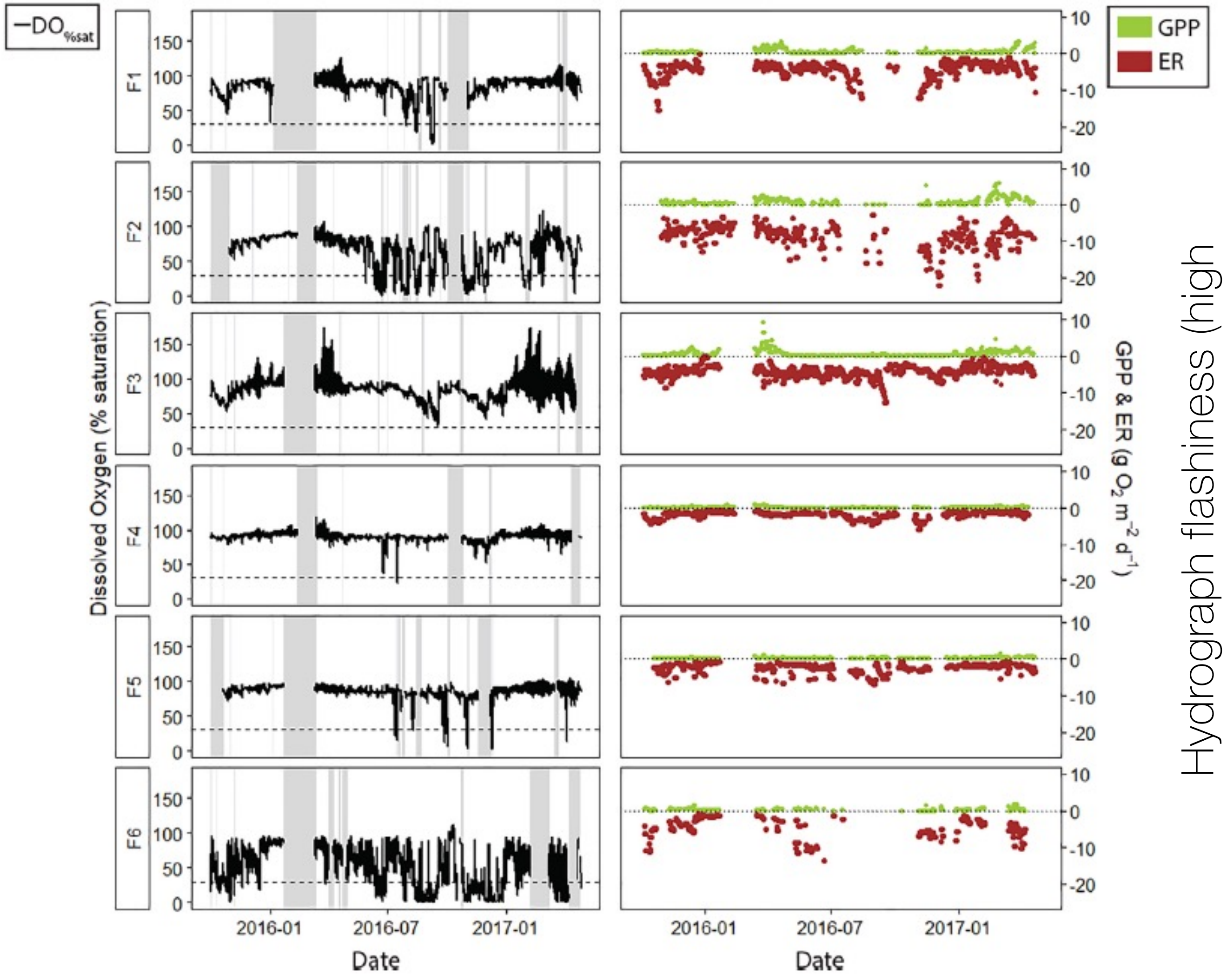
<u>Urban streams</u>: Channelized, little canopy cover, high degree of flashiness, high inputs of organic matter (OM)

- High oxygen deficit
- Rarely supersaturated in oxygen
- Increased probability for hypoxia (DO%<30%)
- Ecosystem health deterioration and biodiversity loss



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EPFL

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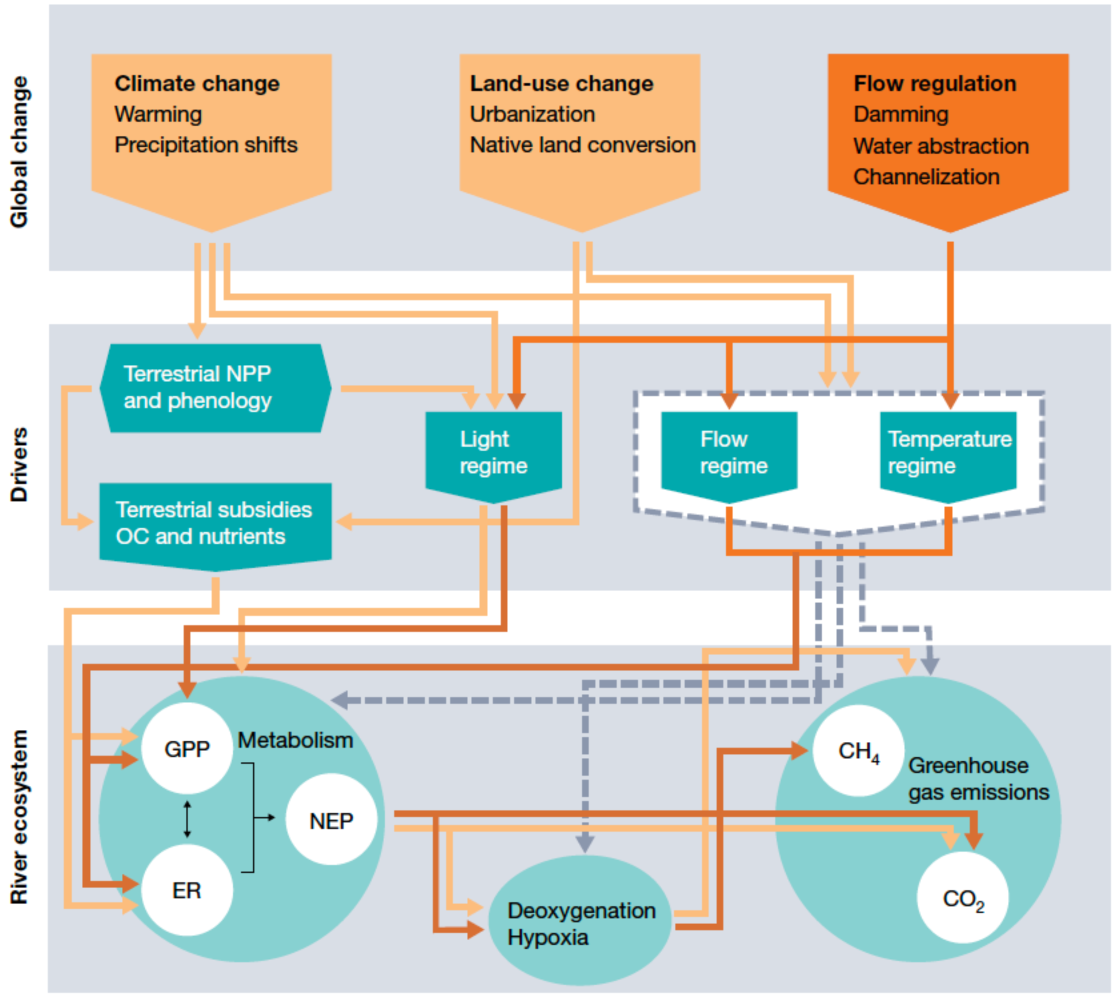
Global change, ecosystem metabolism, deoxygenation and GHG emissions



LIMNOLOGY AND OCEANOGRAPHY
Letters
Open Access
Limnology and Oceanography Letters 8, 2023, 453–463

doi: 10.1002/lol2.10297

LETTER

Extent, patterns, and drivers of hypoxia in the world's streams and rivers

Joanna R. Blaszczak,[1] Lauren E. Koenig,[2a] Francine H. Mejia,[3] Lluís Gómez-Gener,[4] Christopher L. Dutton,[5] Alice M. Carter,[6] Nancy B. Grimm,[7] Judson W. Harvey,[8] Ashley M. Helton,[2] Matthew J. Cohen[9]*

A large number of streams and rivers worldwide threatened by hypoxia (i.e., DO concnetration < 2 mg L^{-1})

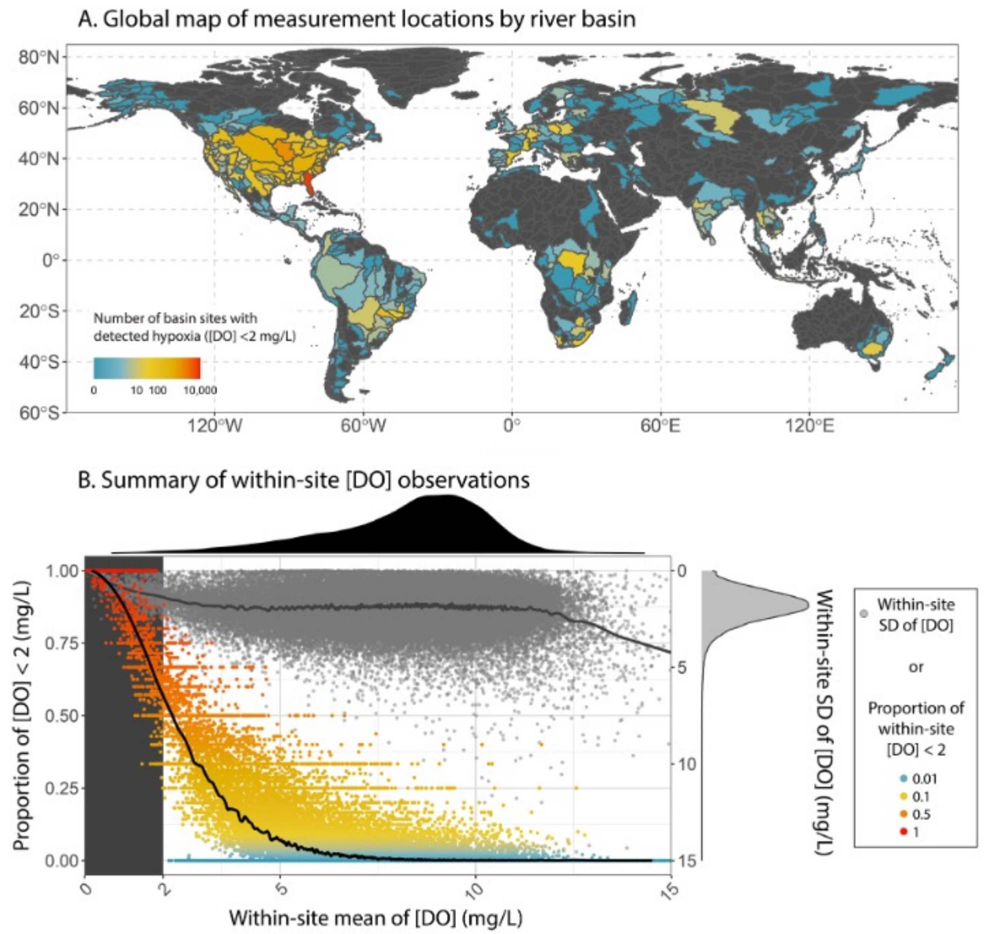


Fig. 1. The global distribution of riverine hypoxia. (**A**) Global map of BasinATLAS level 4 subbasins (Linke et al. 2019) colored by the number of sites within each basin with DO observations < 2 mg DO L^{-1}. *See* Fig. S2 for global map of the proportion of measurements per basin that are hypoxic, and Fig. S3 for the date range for each country. River basins with no DO observations are colored in gray (70% of all global basins). (**B**) Within-site proportion of DO observations that are < 2 mg DO L^{-1} (left *y*-axis) and within-site standard deviation of DO concentration (right *y*-axis; gray points) for sites with at least three measurements (n = 84,010; 67% of all sites). Sixty-two sites with mean DO concentration > 15 mg L^{-1} were excluded from this plot. Loess (locally estimated scatterplot smoothing) lines (black for the proportion of observations that are hypoxic; gray for the standard deviation of DO concentration) have a span of 1% of the dataset. The marginal distribution of within-site mean and standard deviation (SD) of DO concentration are shown at the top in black and the right side of the plot in gray, respectively.

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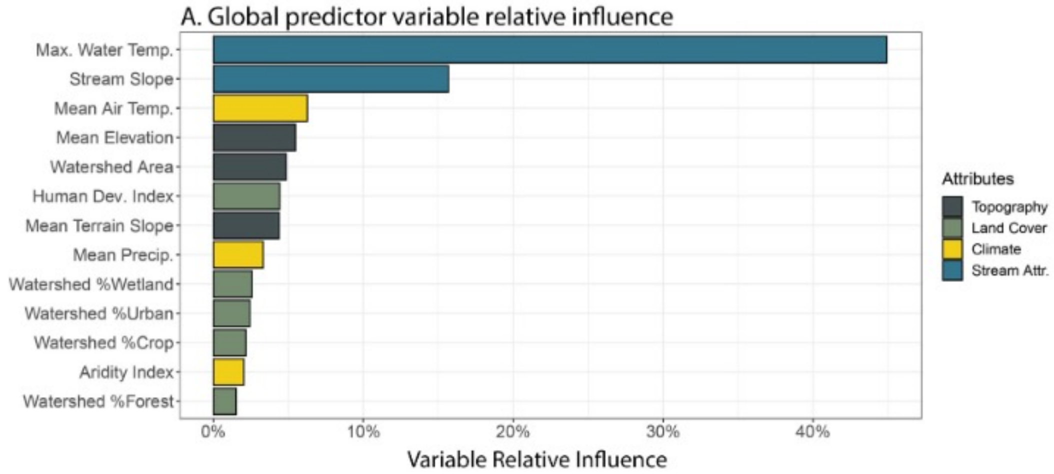
LETTER

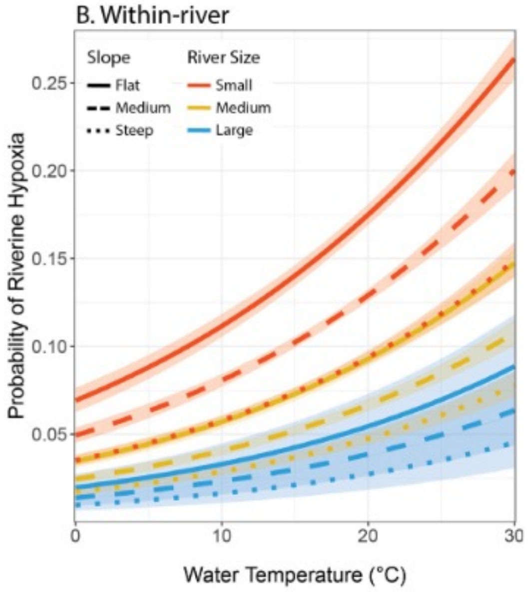
Extent, patterns, and drivers of hypoxia in the world's streams and rivers

Joanna R. Blaszczak[1,*] Lauren E. Koenig[2a] Francine H. Mejia[3] Lluís Gómez-Gener[4] Christopher L. Dutton[5]
Alice M. Carter[6] Nancy B. Grimm[7] Judson W. Harvey[8] Ashley M. Helton[2] Matthew J. Cohen[9]



Maximum water temperature and channel slope as most important predictors for river hypoxia occurrences, followed watershed area, human development index…

Small streams with flat channels are likely most prone to hypoxia as temperature increases



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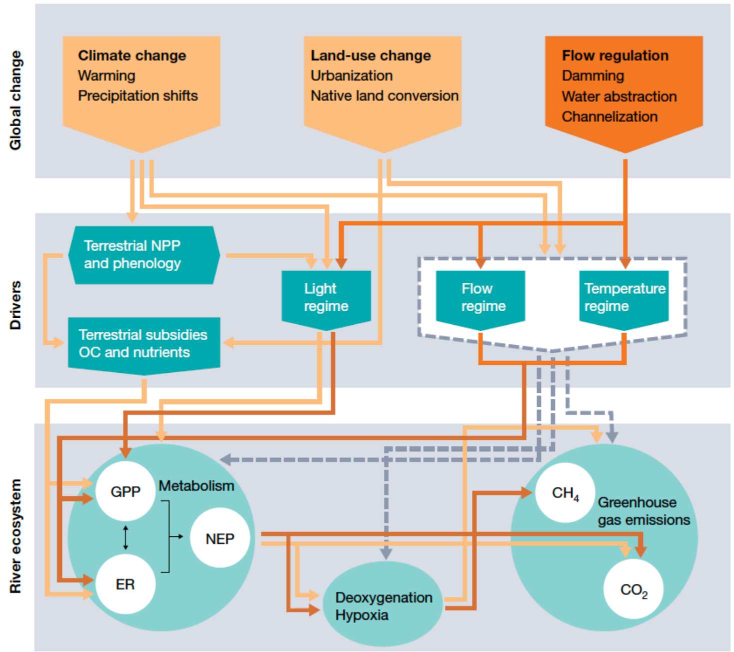


Global change, hypoxia and riverine methane emissions

Article

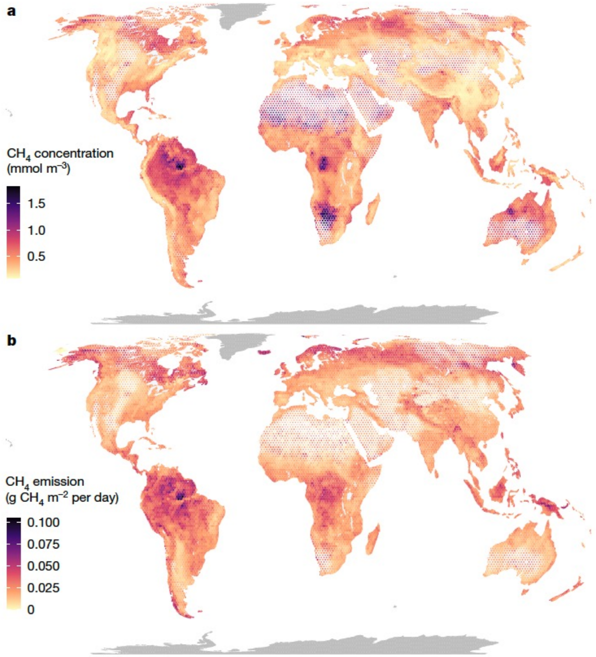
Global methane emissions from rivers and streams

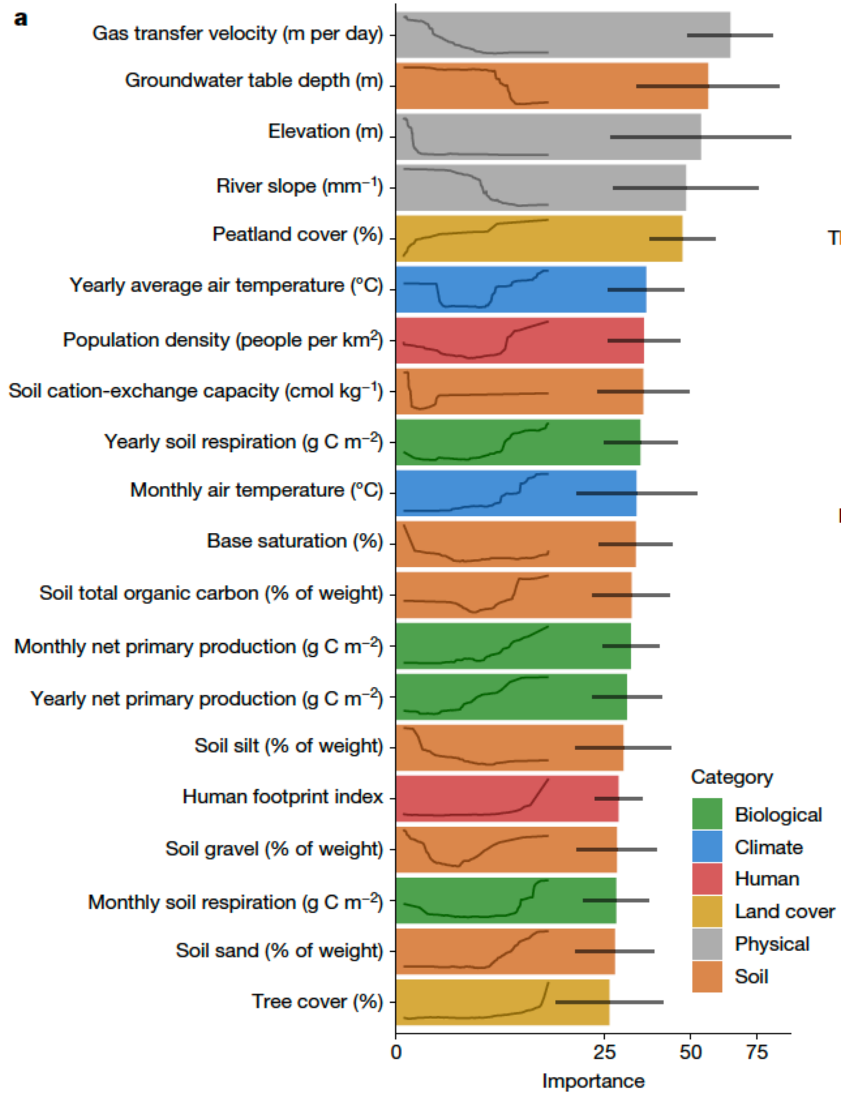
https://doi.org/10.1038/s41586-023-06344-6

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]

- Annual methane emissions of 27.9 (16.7–39.7) Tg CH_4 – comparable to other freshwater ecosystems
- Oxygenation (gas exchange velocity), OM (peatland), temperature and population density as significant predictors of CH_4 concentration





Rivers as a significant source of methane to the atmosphere?

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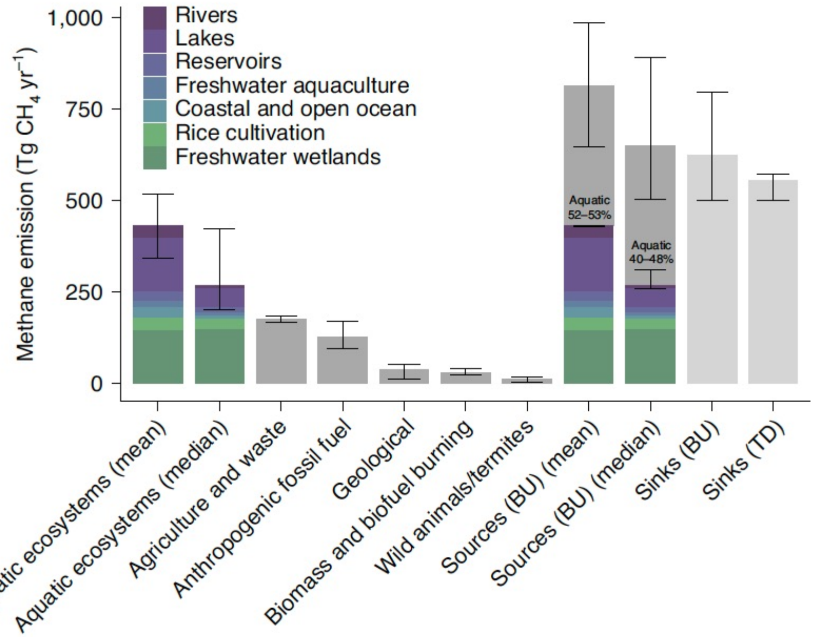
nature geoscience ARTICLES
https://doi.org/10.1038/s41561-021-00715-2

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]

- Half of the global CH_4 emissions from aquatic ecosystems
- High uncertainties related to emission fluxes from various freshwater systems
- Rivers: mean (31 Tg CH_4 yr^{-1}) *versus* median (6 Tg CH_4 yr^{-1})
- Compare to 16.7–39.7 Tg CH_4 yr^{-1} from previous paper



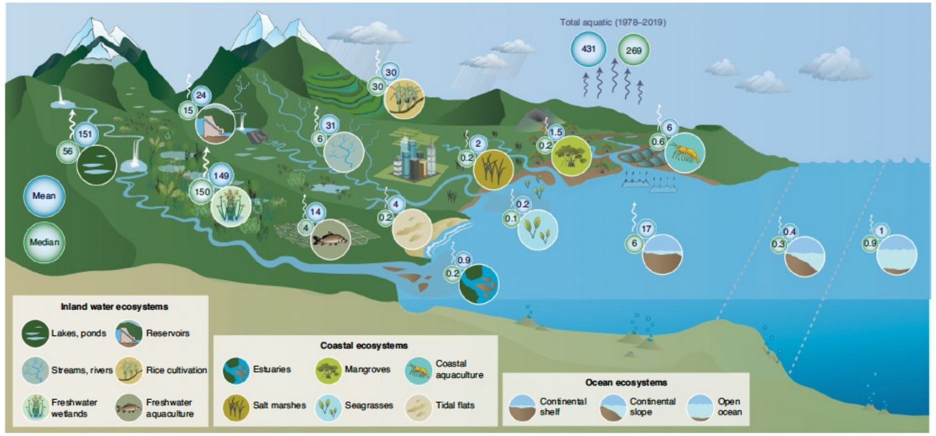
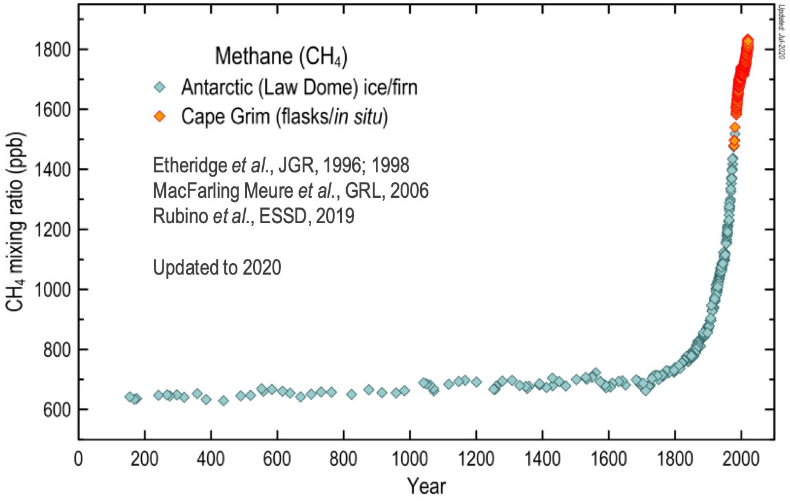


Fig. 3 | Global aquatic methane emissions from headwater streams to the open ocean. Numbers are Tg CH_4 yr^{-1}. Mean emissions are shown in blue circles, and median emissions are shown in green circles. The relative importance of the factors controlling methane distribution and emissions varies along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



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Next class:

Nutrient dynamics and cycling

….

LIMNOLOGY and OCEANOGRAPHY

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Limnol. Oceanogr. 63, 2018, S99–S118

doi: 10.1002/lno.10726

The metabolic regimes of flowing waters

E. S. Bernhardt,[1*] J. B. Heffernan,[2] N. B. Grimm,[3] E. H. Stanley,[4] J. W. Harvey,[5] M. Arroita,[6,7] A. P. Appling,[8] M. J. Cohen,[9] W. H. McDowell,[10] R. O. Hall, Jr.,[7,a] J. S. Read,[11] B. J. Roberts,[12] E. G. Stets,[13] C. B. Yackulic[14]

- Ecosystem GPP affects drive concentration of nitrate in streams
- Primary procuders rely on inorganic nitrogen for growth
- Extend of spring blooms shape annual nitrogen uptake
- Overall low during summer because of shading through canopy

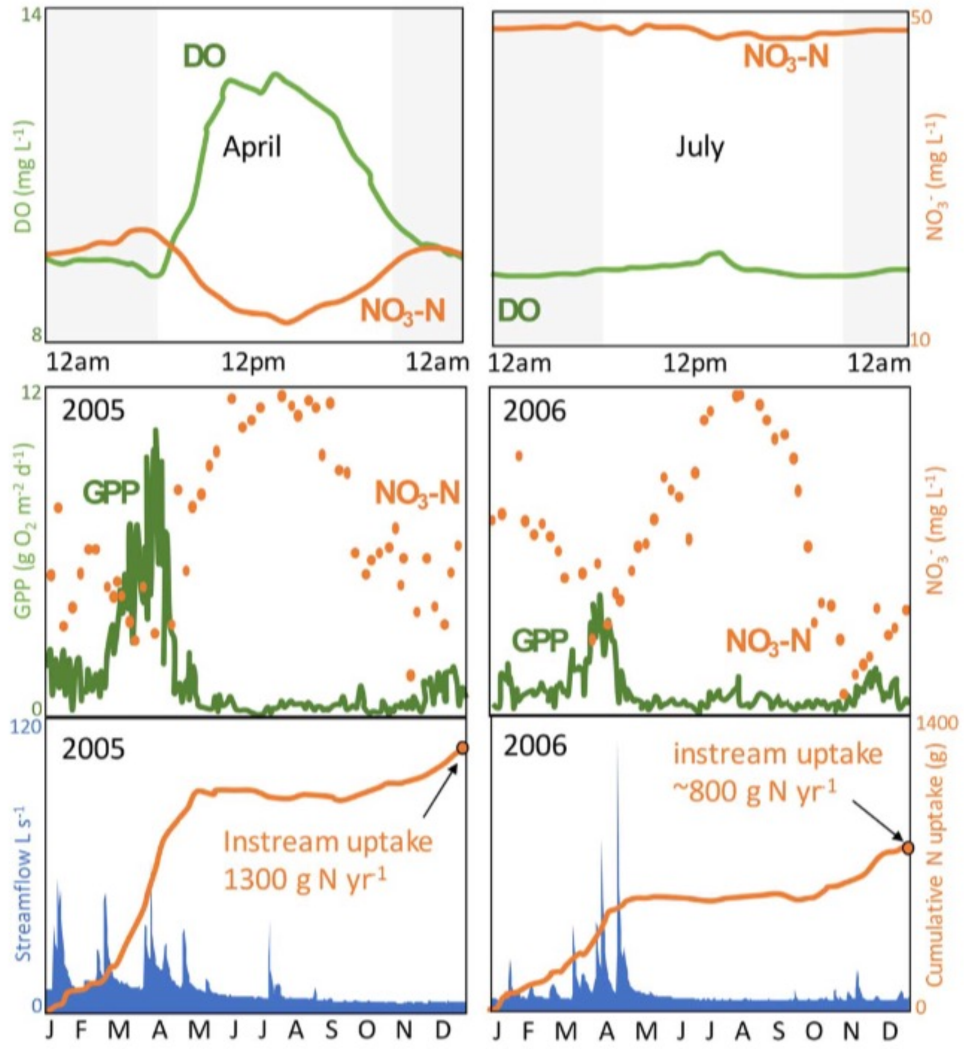

Fig. 6. Data collected from Walker Branch watershed in Oak Ridge Tennessee (Roberts and Mulholland 2007; Roberts et al. 2007; Lutz et al. 2012). Upper panels during periods of the year with high GPP, diel increases in dissolved oxygen are linked to diel declines in stream nitrate concentrations while nitrate concentrations are constant (and elevated) during summer months when the forest canopy is closed. Middle panels: Seasonal variation in GPP explains the low stream nitrate concentrations during spring and fall. Lower panels: Years with larger spring algal blooms (e.g., 2005) have greater total annual instream nitrogen uptake than years in which spring storms reduce the longevity and peak productivity of spring algae (e.g., 2006).

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