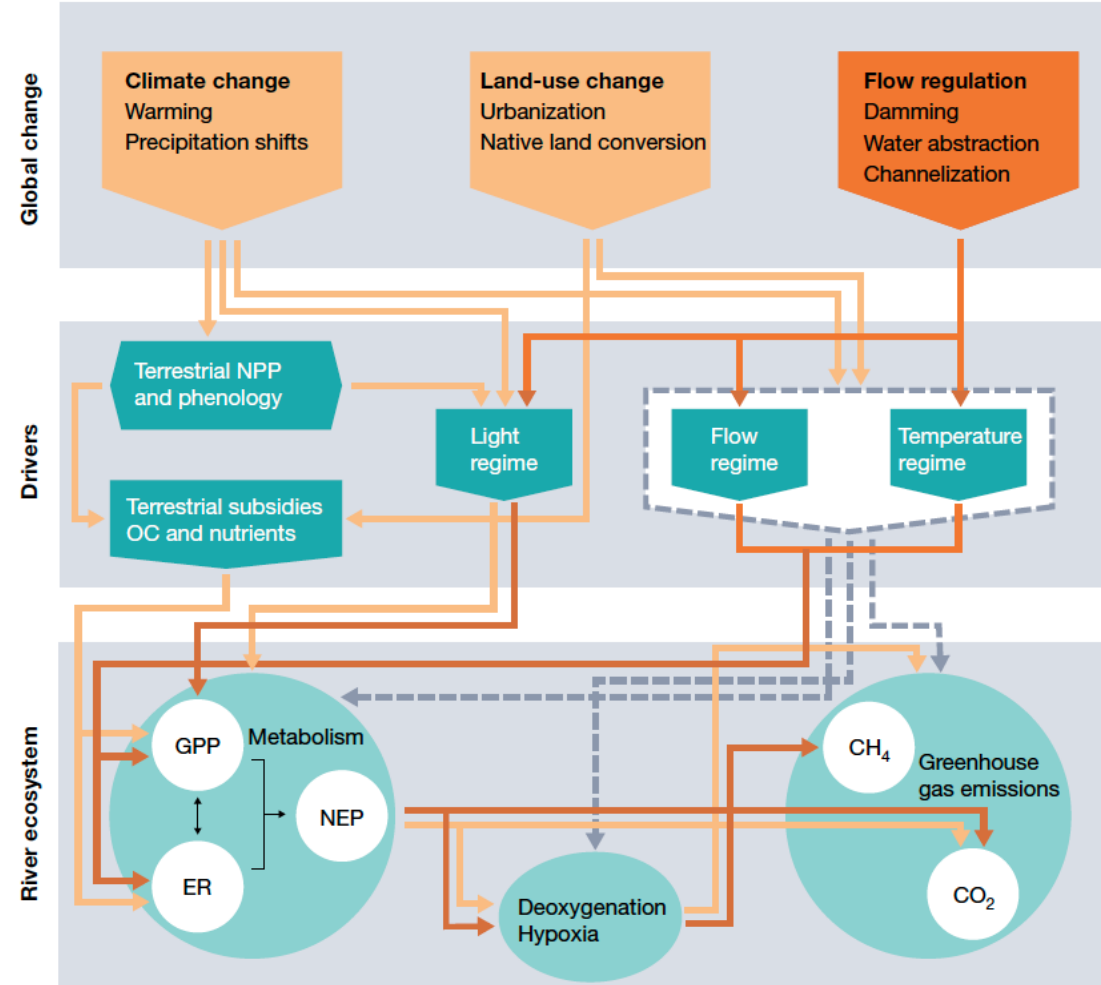


River ecosystem metabolism and carbon biogeochemistry in a changing world

Tom J. Battin¹, Ronny Lauerwald², Emily S. Bernhardt³, Enrico Bertuzzo⁴, Lluís Gómez Gener⁵, Robert O. Hall Jr⁶, Erin R. Hotchkiss⁷, Taylor Masvara⁸, Tamlin M. Pavelsky⁹, Lishan Ran¹⁰, Peter Raymond¹¹, Judith A. Rosentreter¹² & Pierre Regnier¹⁴

Global change, ecosystem metabolism, deoxygenation and GHG emissions



LETTER

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

Joanna R. Blaszczak¹, Lauren E. Koenig², Francine H. Mejia³, Lluís Gómez-Gener⁴, Christopher L. Dutton⁵,
Alice M. Carter⁶, Nancy B. Grimm⁷, Judson W. Harvey⁸, Ashley M. Helton⁹, Matthew J. Cohen¹⁰

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

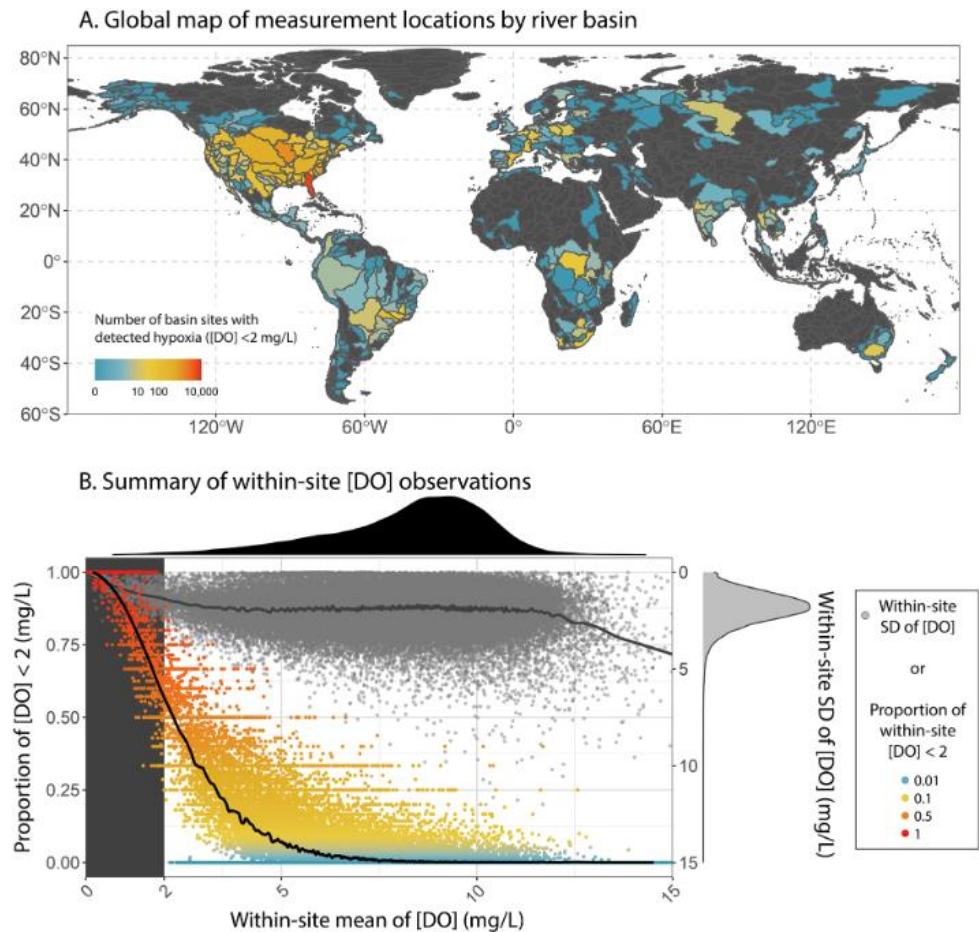


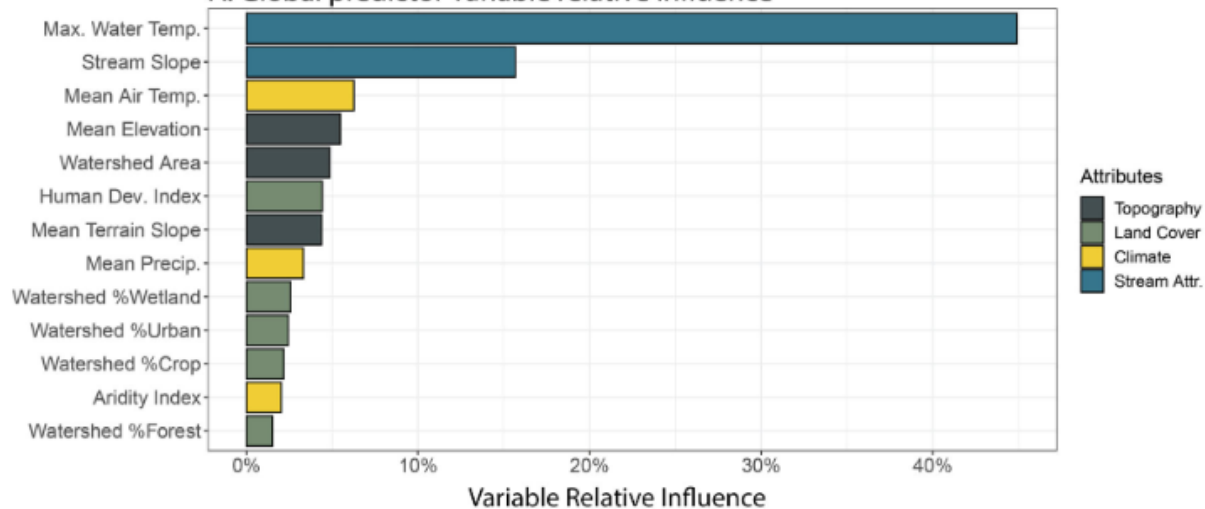
Fig. 1. The global distribution of riverine hypoxia. **(A)** Global map of BasinATLAS level 4 subbasins (Linke et al. 2019) colored by the number of sites within each basin with DO observations $< 2 \text{ mg DO L}^{-1}$. See Fig. S2 for global map of the proportion of measurements per basin that are 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 $< 2 \text{ mg DO L}^{-1}$ (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 $> 15 \text{ mg L}^{-1}$ 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.

LETTER

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

Joanna R. Blaszczak¹, Lauren E. Koenig^{2,3}, Francine H. Mejia⁴, Lluís Gómez-Gener⁵, Christopher L. Dutton⁵, Alice M. Carter⁶, Nancy B. Grimm⁷, Judson W. Harvey⁸, Ashley M. Helton⁹, Matthew J. Cohen⁹

A. Global predictor variable relative influence



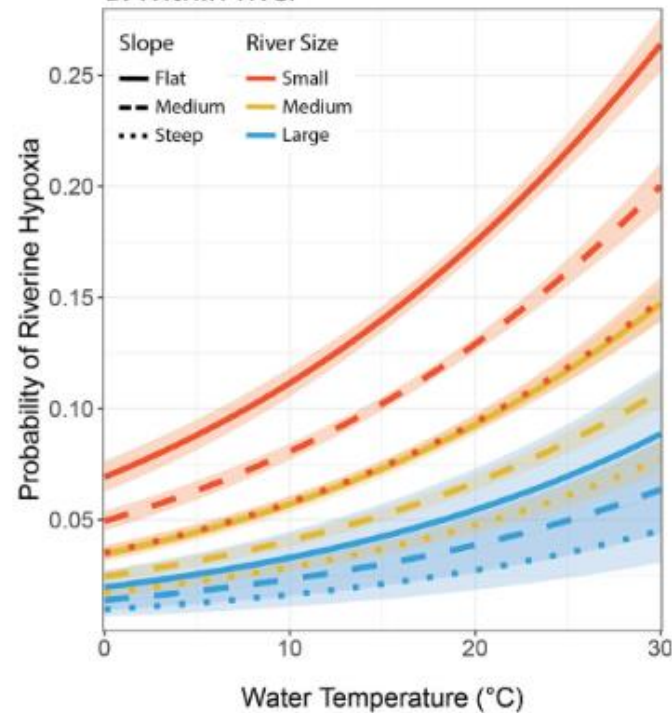
Maximum water temperature and channel slope as most important predictors for river hypoxia occurrences, followed watershed area, human development index...

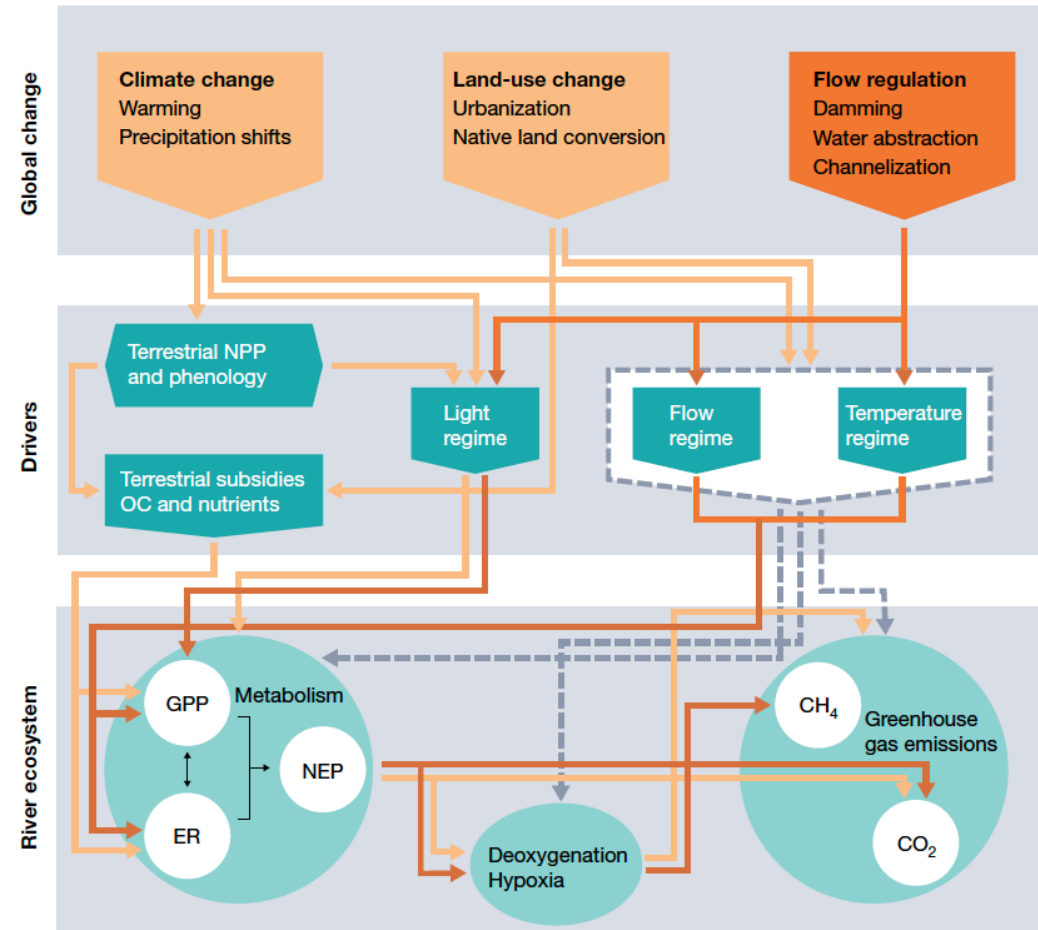
Small streams with flat channels are likely most prone to hypoxia as temperature increases

Why?

Flat and small: gas exchange and terrestrial subsidies

B. Within-river





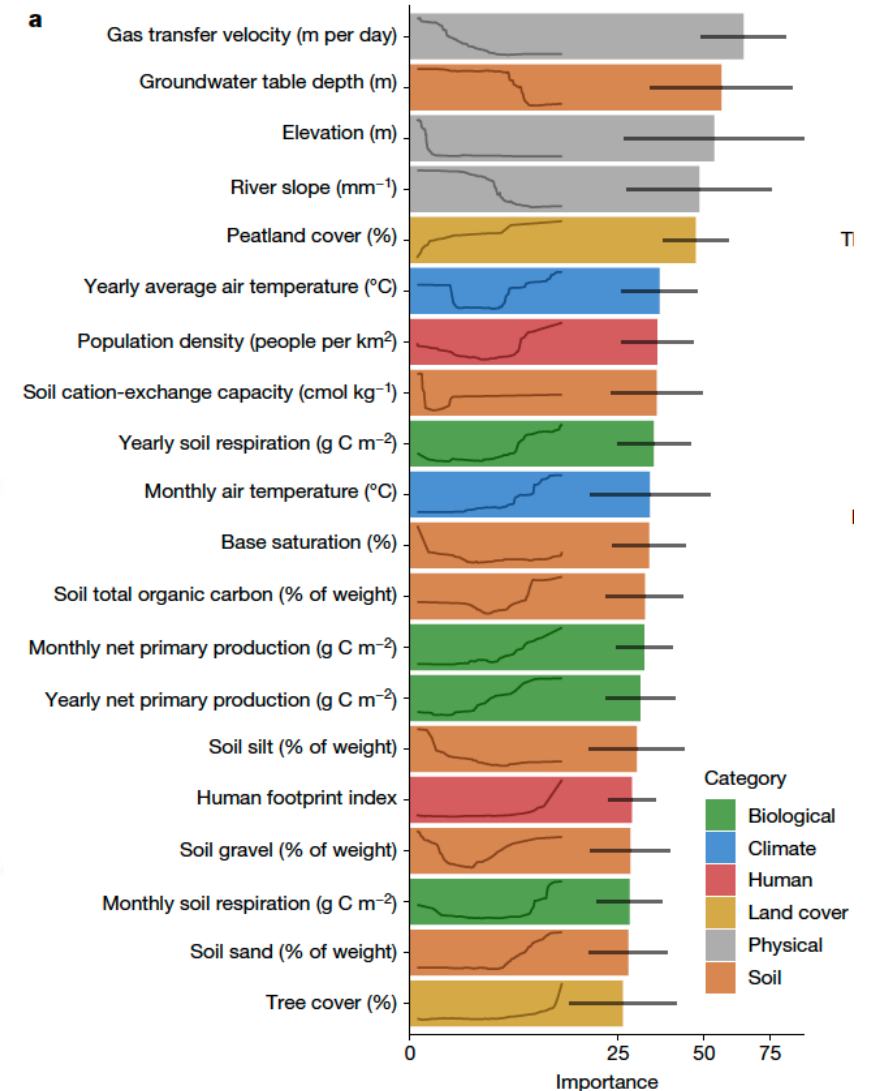
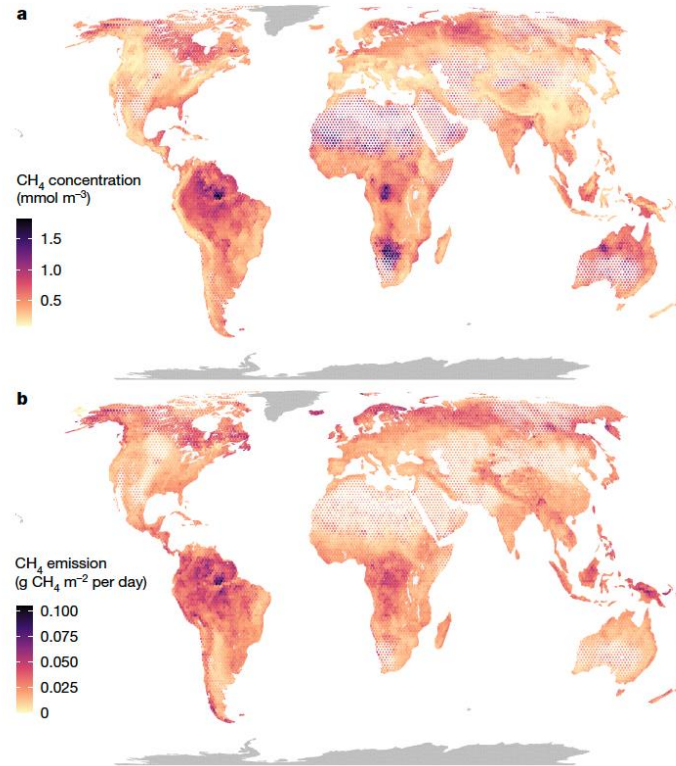
Global change, hypoxia and riverine methane emissions
 Anaerobic metabolism — methanogenesis

Global methane emissions from rivers and streams

<https://doi.org/10.1038/s41586-023-06344-6> Gerard Rocher-Ros^{1,2,3}, Emily H. Stanley⁴, Luke C. Loken⁵, Nora J. Casson⁶, Peter A. Raymond⁷, Shaoda Liu⁸, Giuseppe Amattuli⁷ & Ryan A. Sponseller¹

Received: 25 October 2022

- Annual methane emissions of 27.9 (16.7–39.7) Tg CH₄ — comparable to other freshwater ecosystems
- Oxygenation (gas exchange velocity), organic carbon (peatland), temperature and population density as significant predictors of CH₄ concentration



Rivers as a significant source of methane to the atmosphere

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

Judith A. Rosentreter^{1,2}, Alberto V. Borges³, Bridget R. Deemer⁴, Meredith A. Holgerson^{5,6,7}, Shaoda Liu^{2,8}, Chunlin Song^{9,10}, John Melack¹¹, Peter A. Raymond², Carlos M. Duarte^{12,13}, George H. Allen¹⁴, David Olefeldt¹⁵, Benjamin Poulter¹⁶, Tom I. Battin¹⁷ and Bradley D. Eyre¹

- Half of the global CH₄ emissions from aquatic ecosystems
- High uncertainties related to emission fluxes from various freshwater systems
- Rivers: mean (31 Tg CH₄ yr⁻¹) versus median (6 Tg CH₄ yr⁻¹)
- Compare to 16.7–39.7 Tg CH₄ yr⁻¹ from previous paper

Steady increase of methane emissions

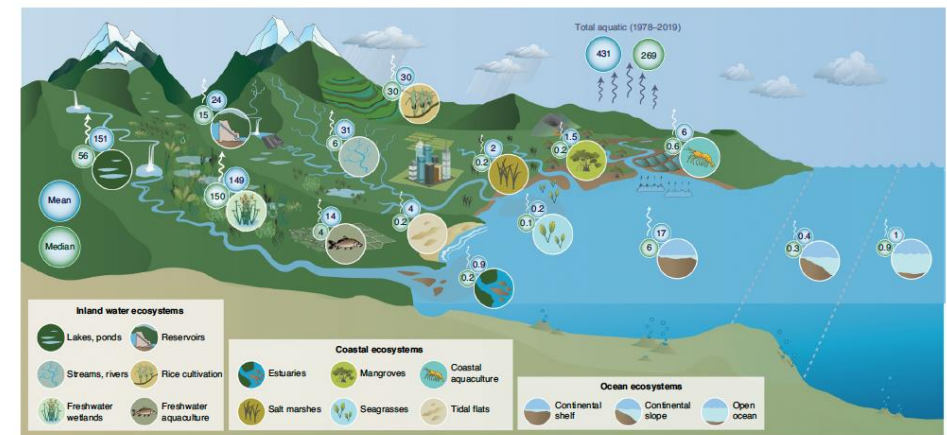
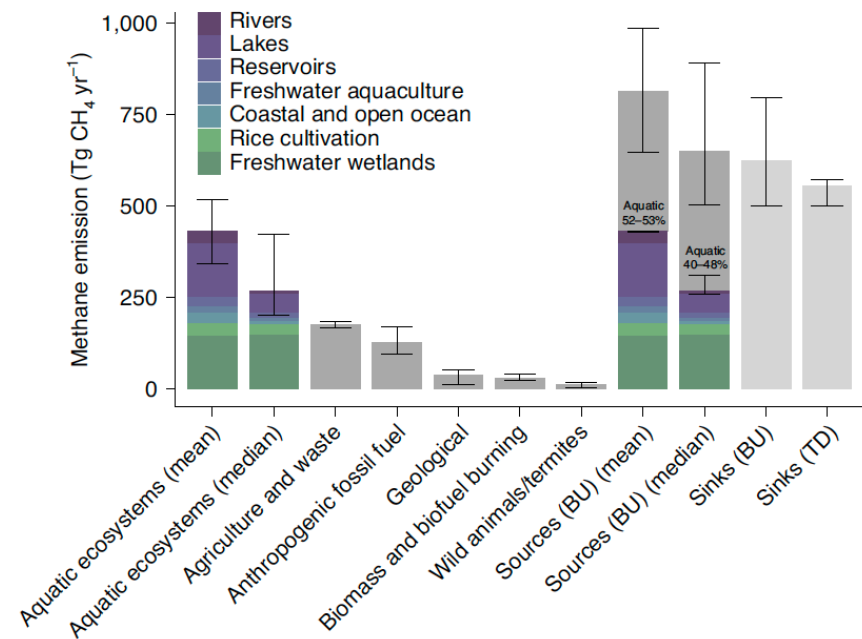
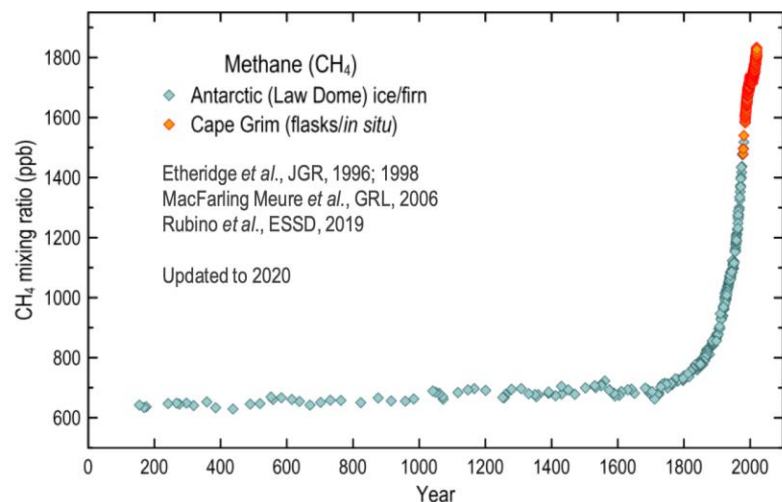
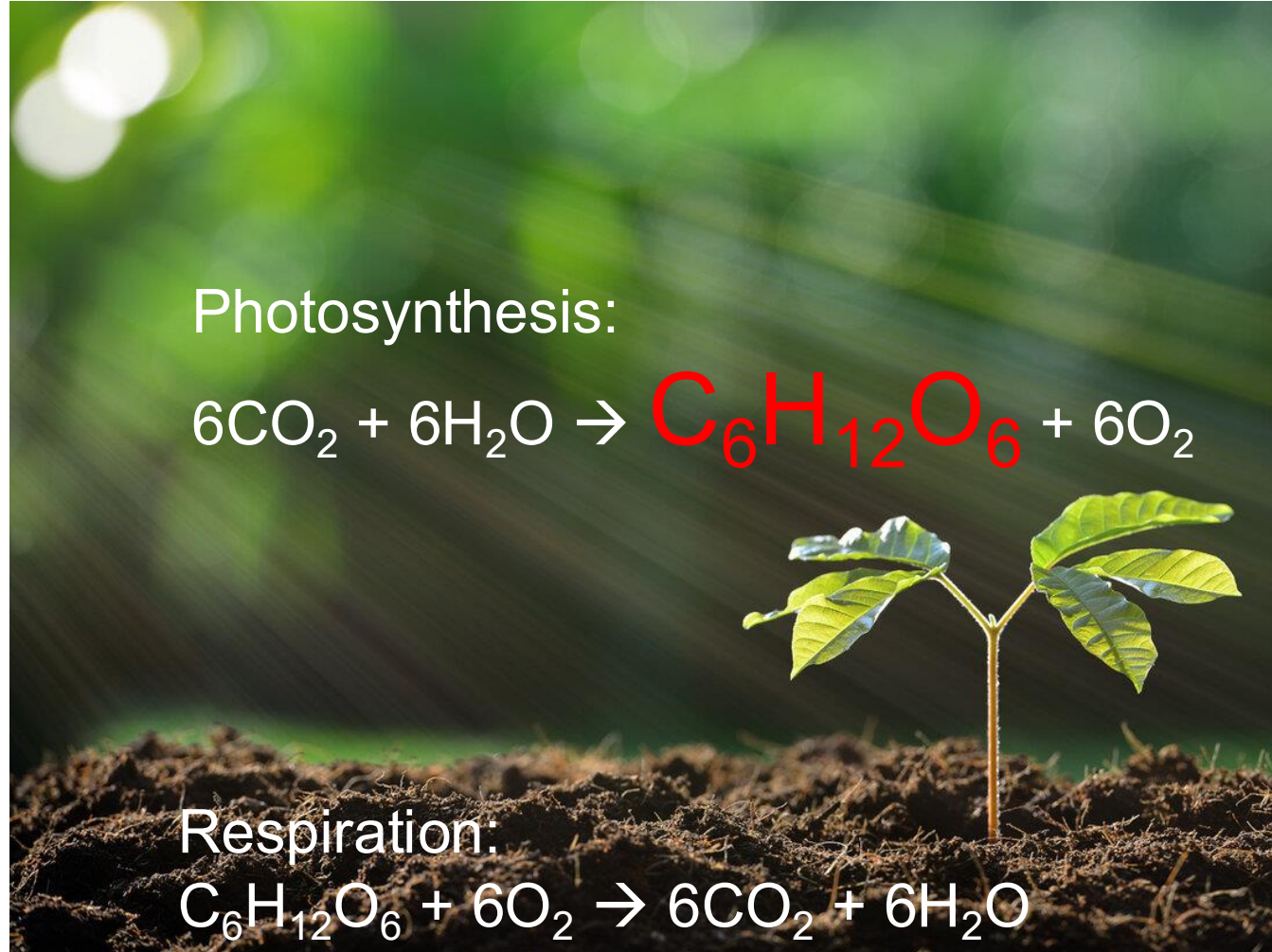


Fig. 3 | Global aquatic methane emissions from headwater streams to the open ocean. Numbers are Tg CH₄ yr⁻¹. Mean emissions are shown in blue circles, and median emissions are shown in green circles. The relative importance of the factors controlling methane distribution and emissions varies along the land-ocean aquatic continuum.

What happens to all the organic carbon in a changing world?



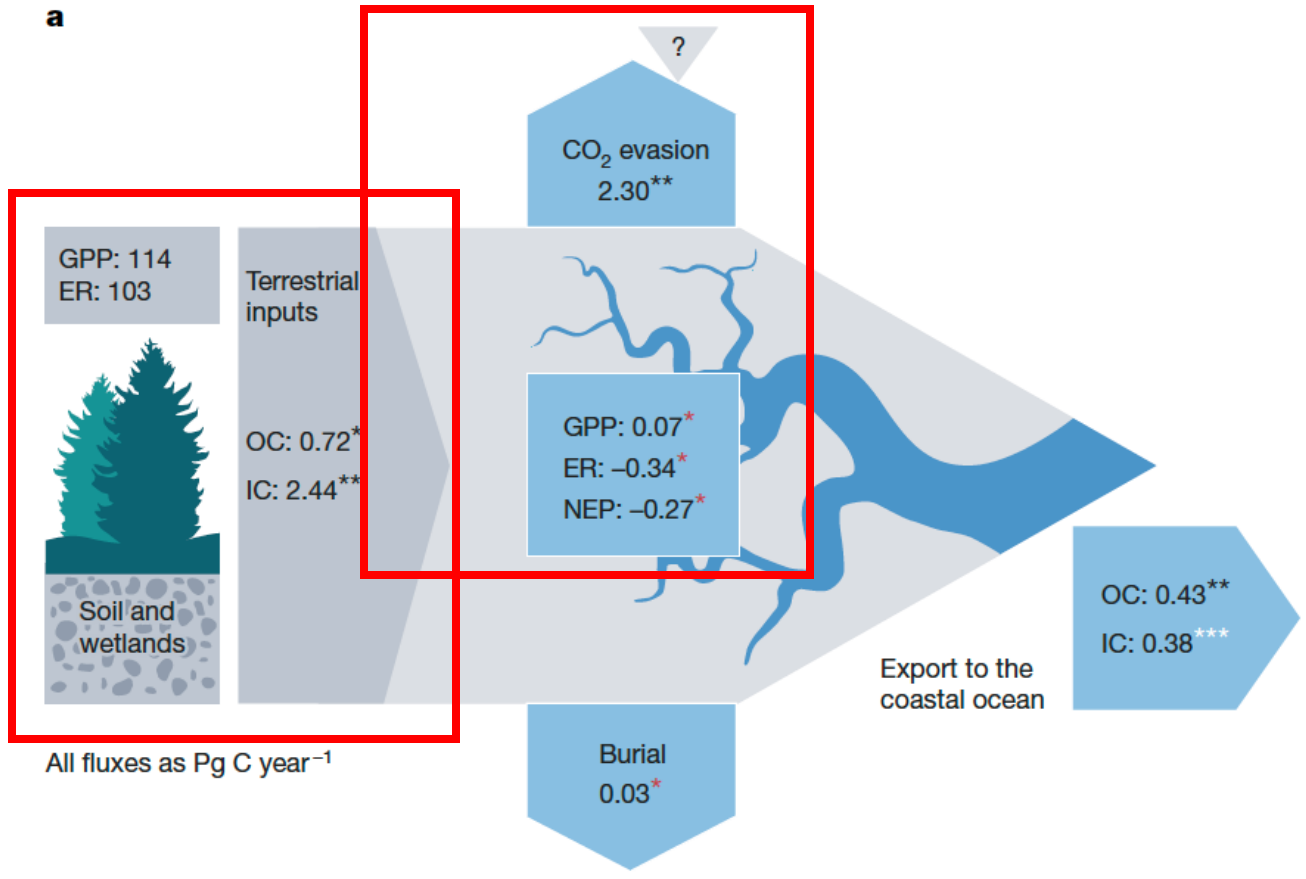
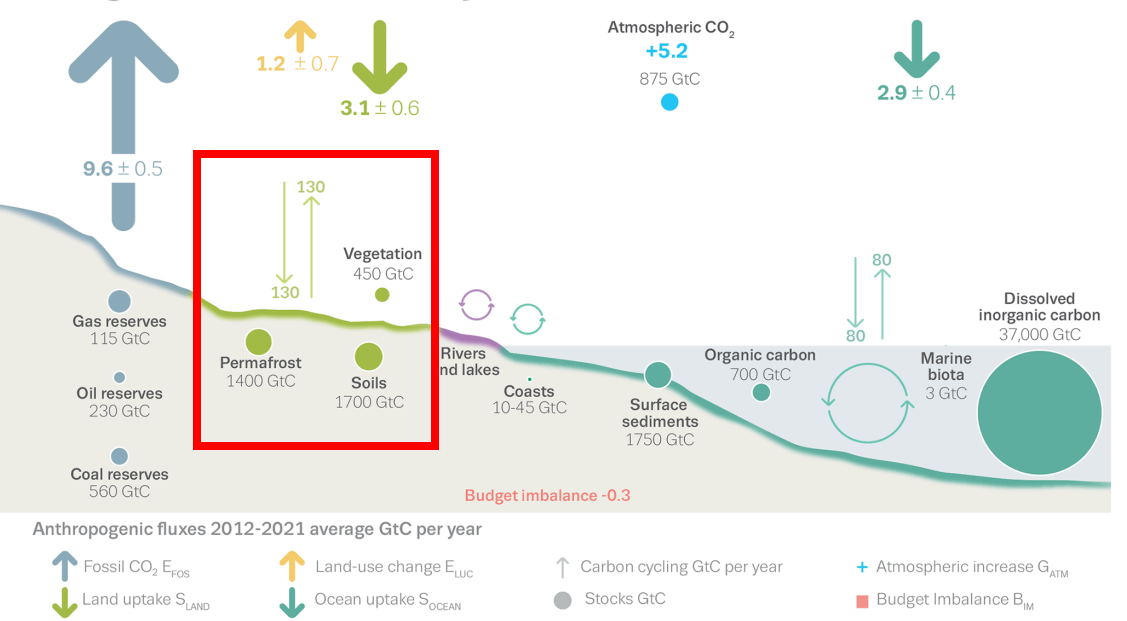
Photosynthesis:

$$6\text{CO}_2 + 6\text{H}_2\text{O} \rightarrow \text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2$$

Respiration:

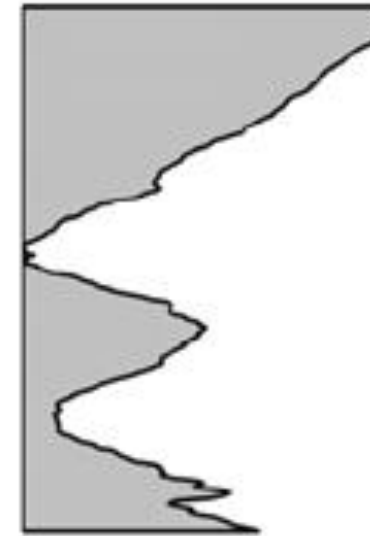
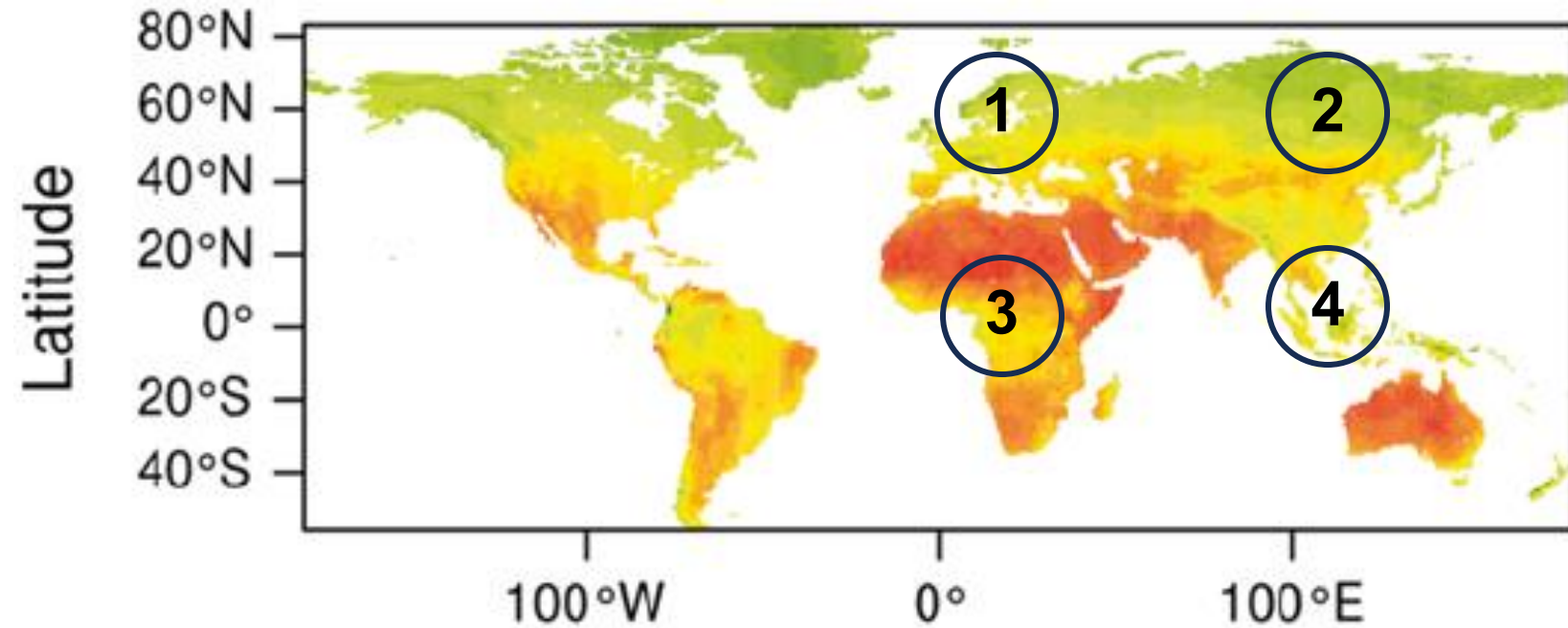
$$\text{C}_6\text{H}_{12}\text{O}_6 + 6\text{O}_2 \rightarrow 6\text{CO}_2 + 6\text{H}_2\text{O}$$

The global carbon cycle

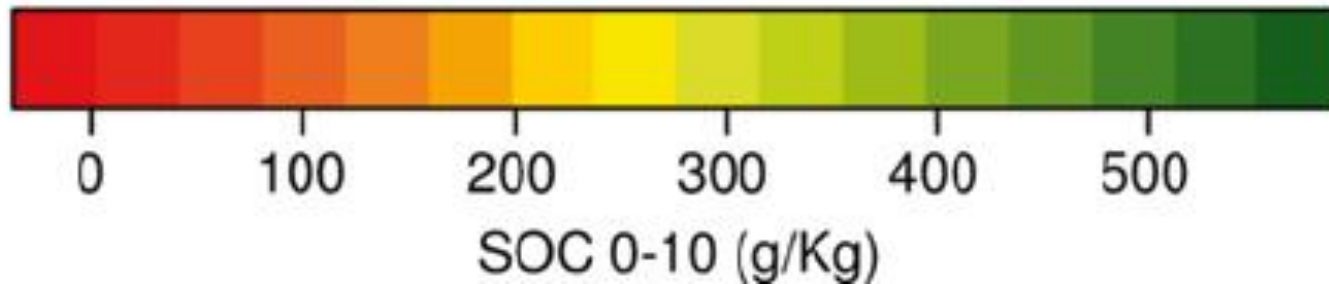


- Terrestrial stores of organic carbon
- Mobilisation and transportation
- Transformation by aquatic metabolism
- Evasion as CO₂ and CH₄ into the atmosphere

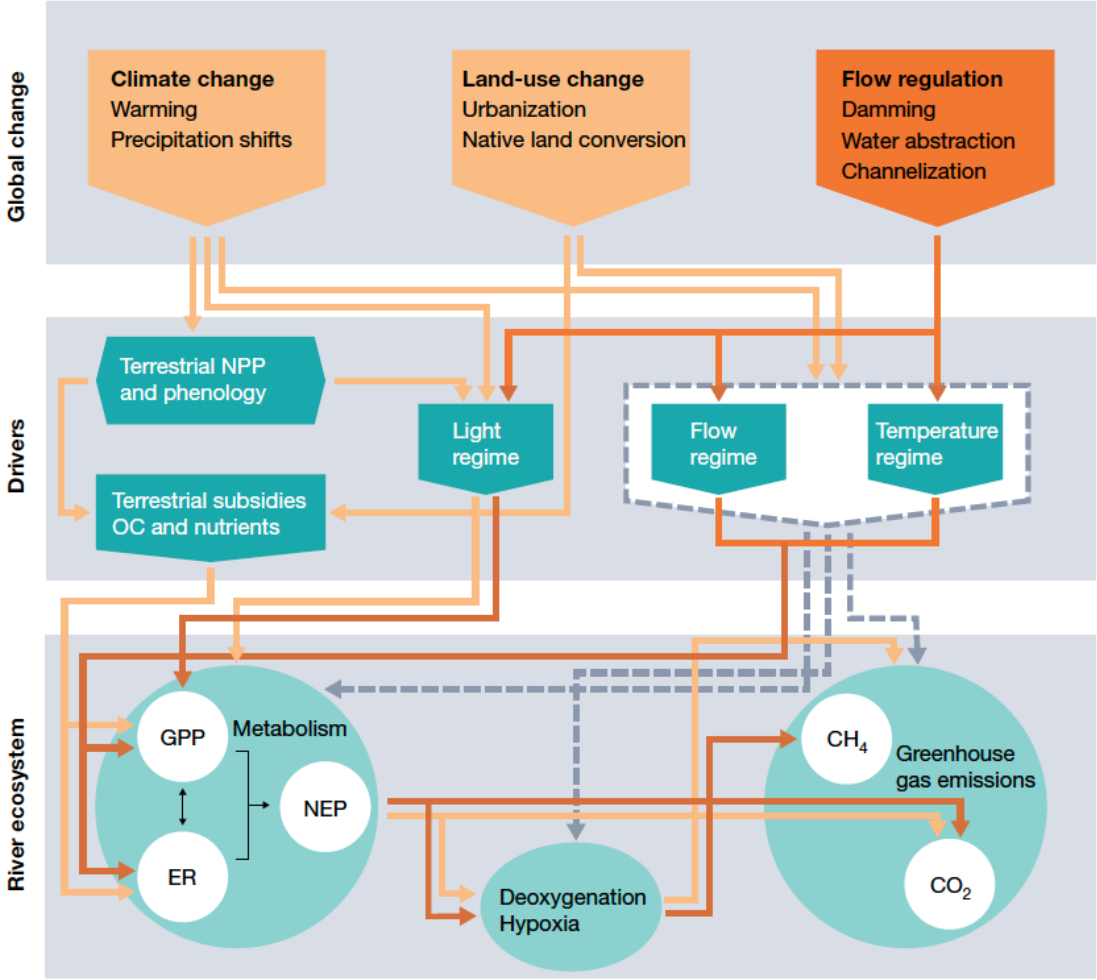
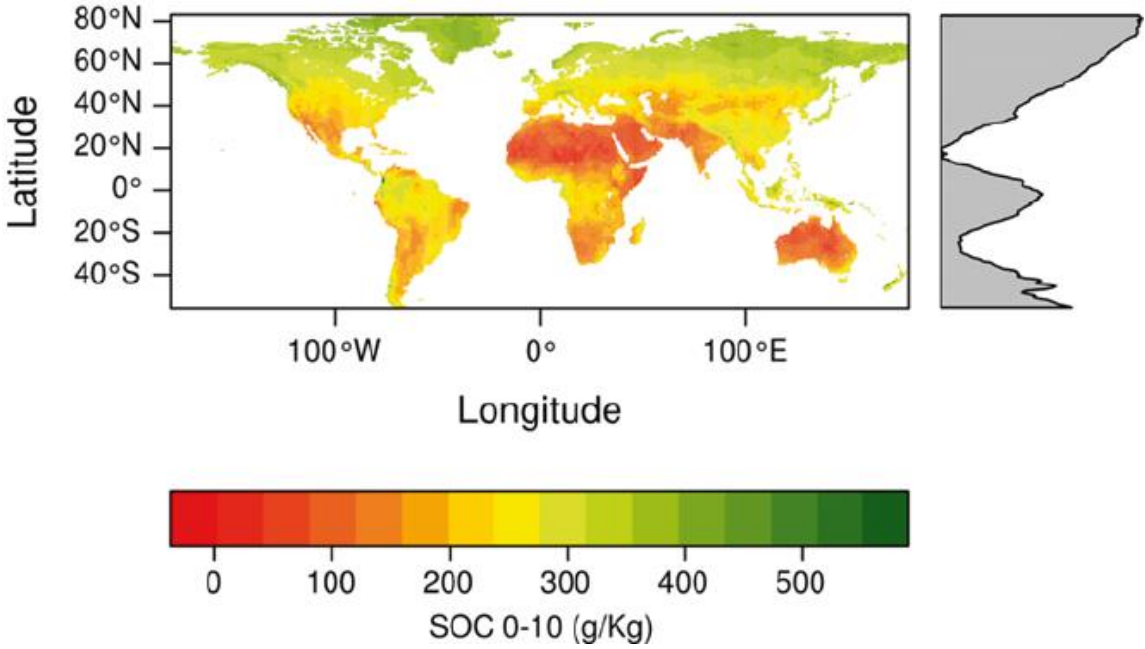
Global distribution of soil organic carbon (SOC)



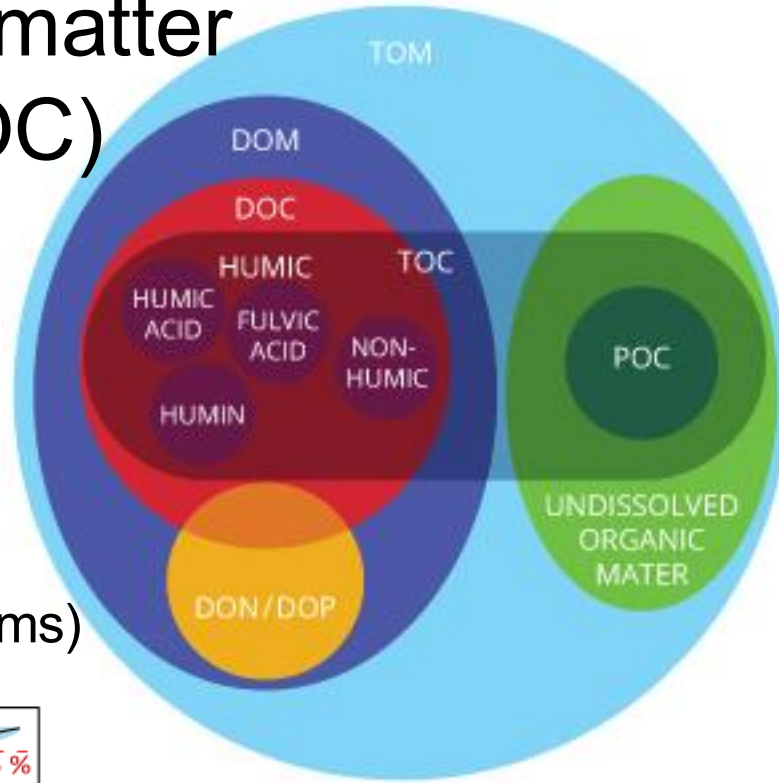
1. Boreal forests in Scandinavia
2. Permafrost in Siberia
3. Peat in Southeast Asia
4. Soils in the Congo basin



Understanding the links between global change and biogeochemistry across ecosystems



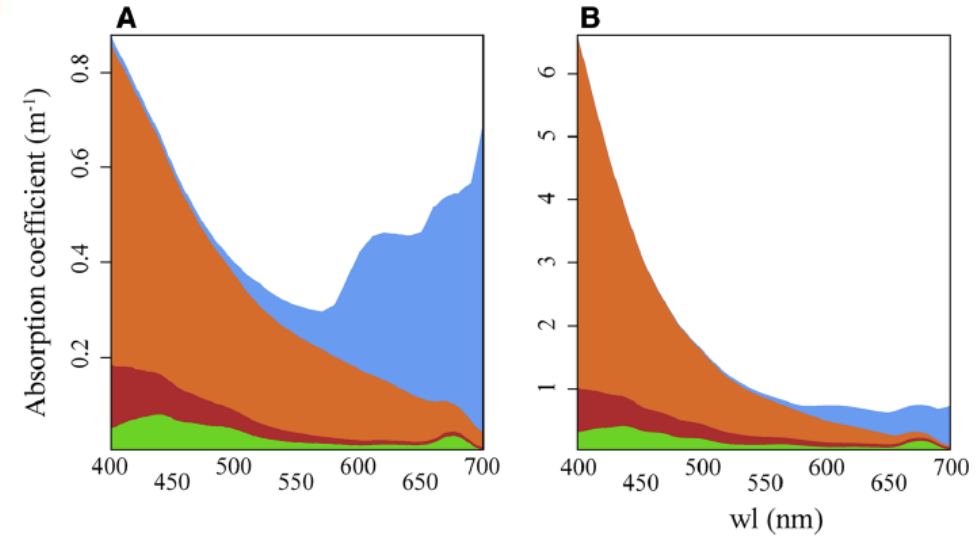
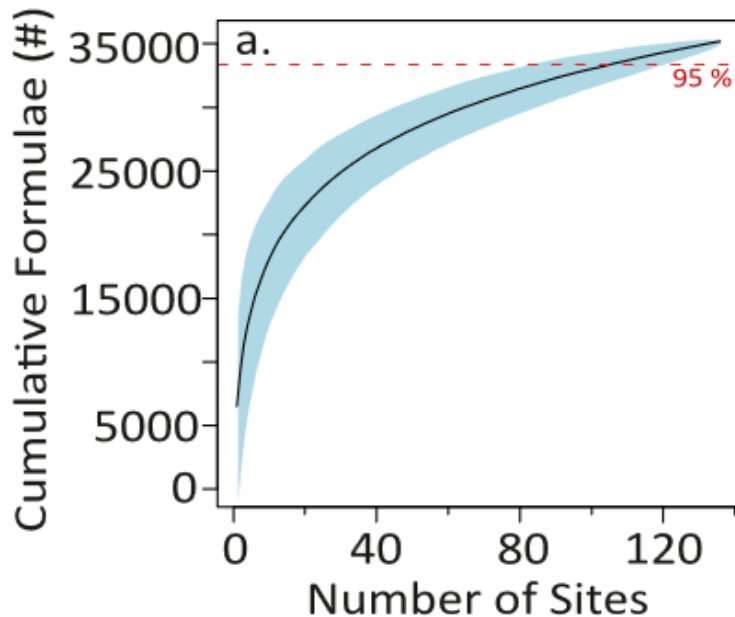
Dissolved organic matter (more than just DOC)



Chromophoric DOM (humics and fulvics)



Highly diverse molecular
composition (glacier-fed streams)



Each colored area represents the absorption spectrum

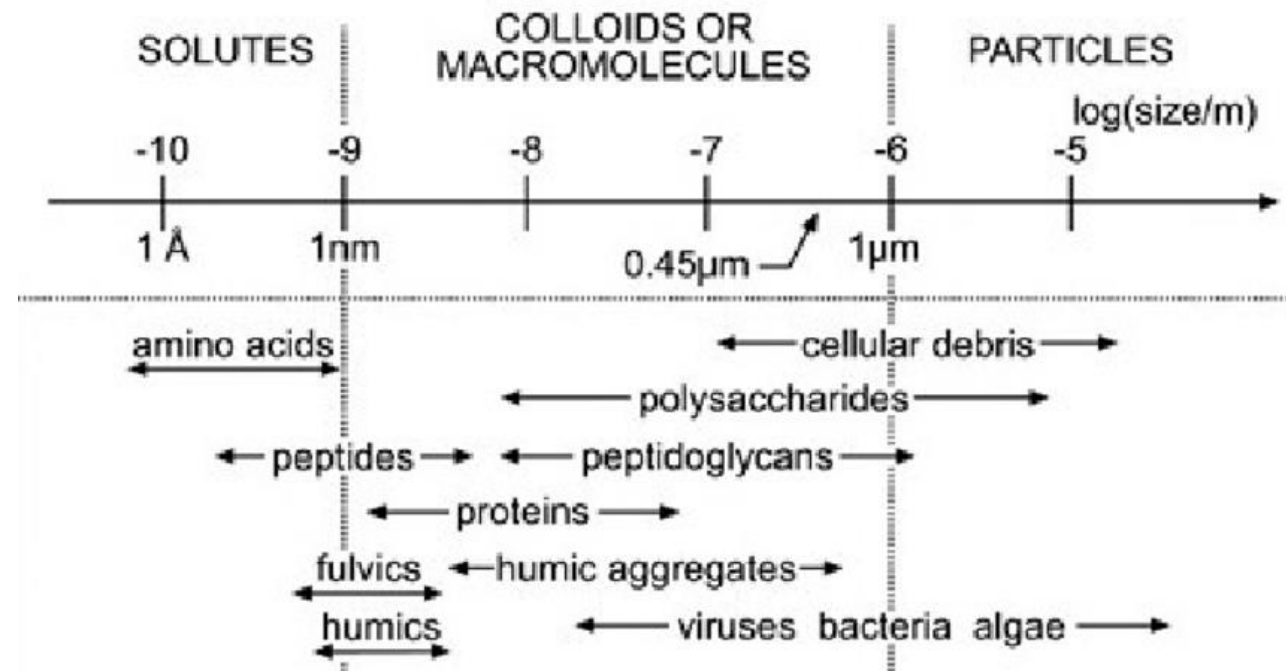
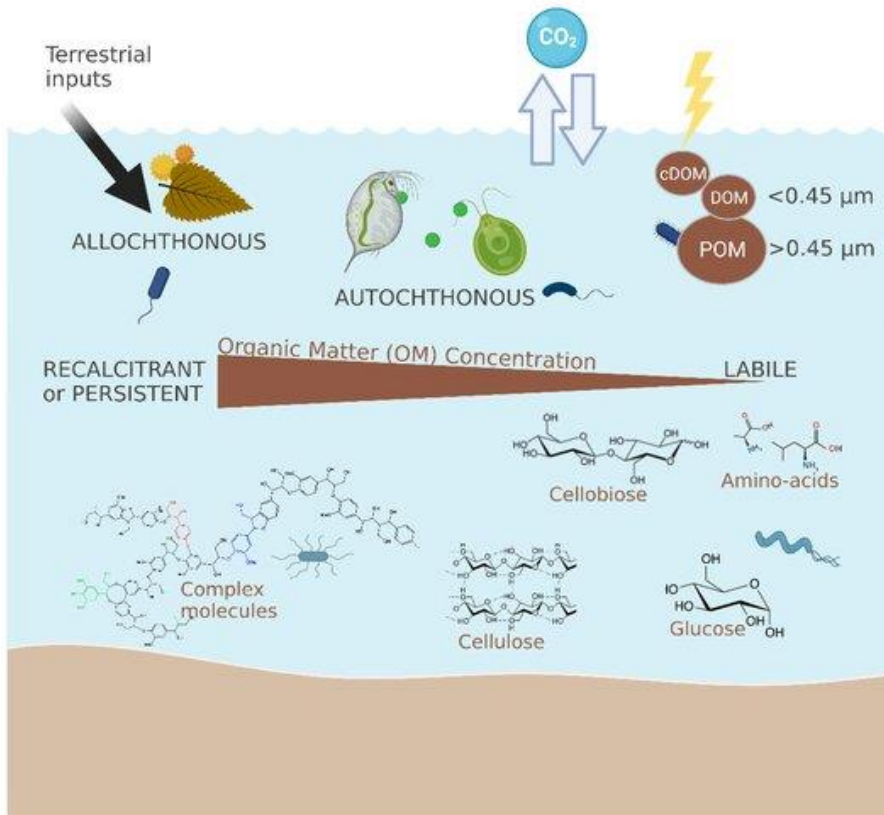
- phytoplankton: green
- non-algal particles: dark brown
- chromophoric DOM: light brown
- water: blue

Dissolved organic matter (more than just DOC)



DOM: The major intermediary to the carbon cycle

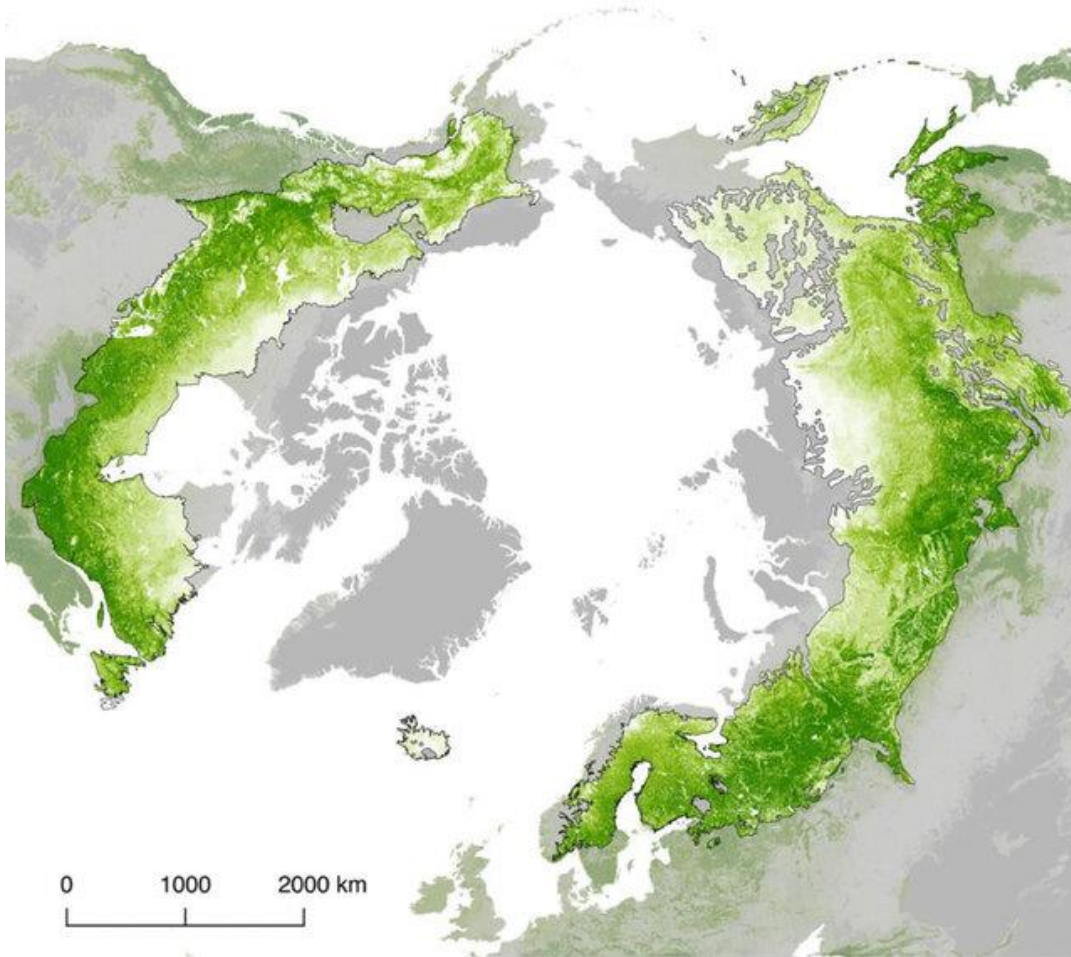
- Chemistry (elemental composition)
- Light absorption
- Size (degree of polymerisation)
- Bioavailability (labile or persistent)



Is there a link between boreal forests and fish populations in the Atlantic Ocean?



Terrestrial greening and aquatic browning



Greening of the boreal landscape
Increasing primary production

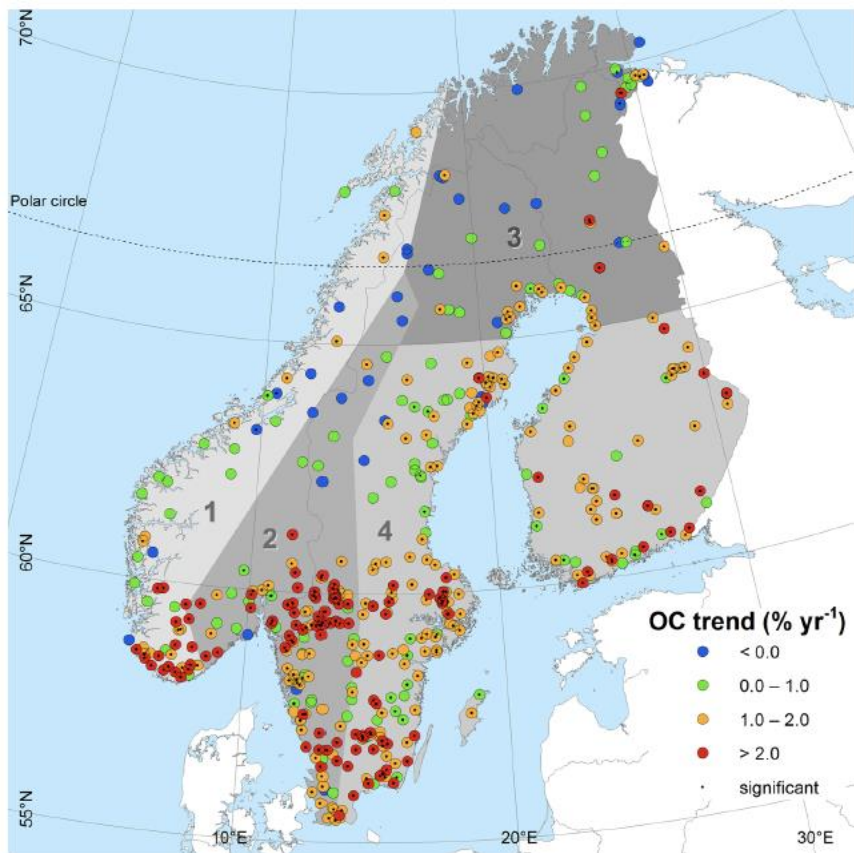


- Large amounts of soil organic carbon mobilized and entering streams and rivers
- Humic and fulvic acids (degradation product of vascular plant material) induce browning of surface waters
- Increases in water DOC concentration



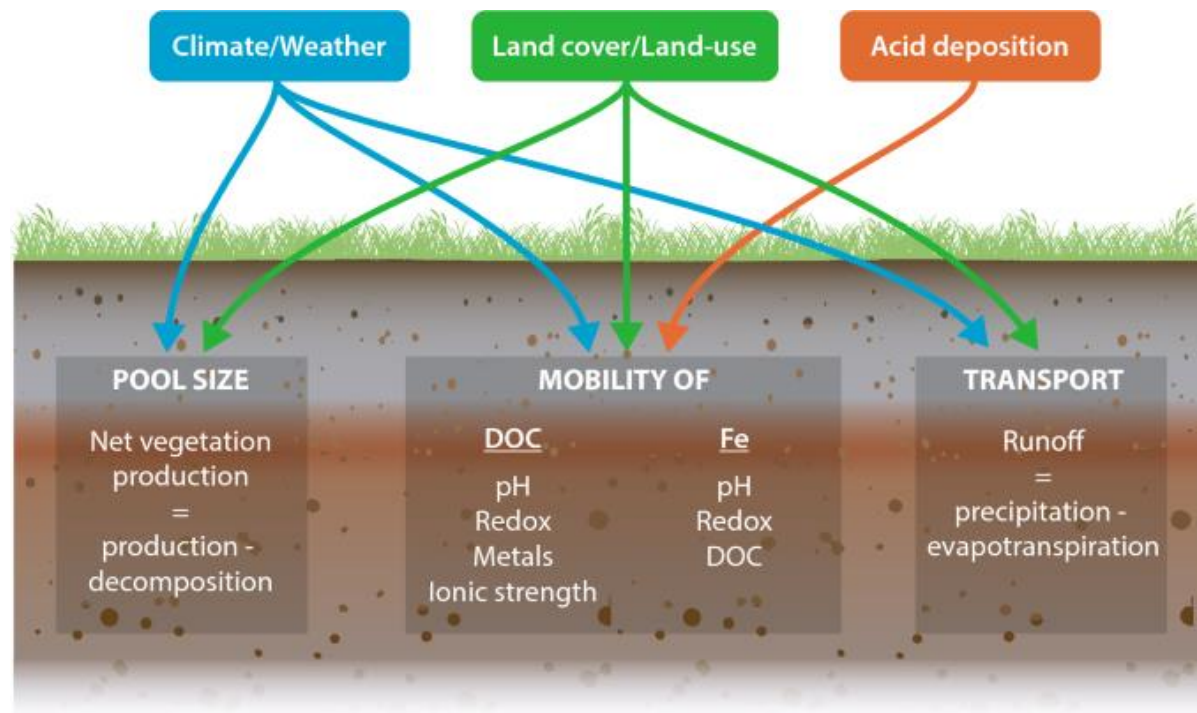
Current Browning of Surface Waters Will Be Further Promoted by Wetter Climate

Heleen A. de Wit,^{*,†} Salar Valinia,[†] Gesa A. Weyhenmeyer,[‡] Martyn N. Futter,[§] Pirkko Kortelainen,^{||} Kari Austnes,[†] Dag O. Hessen,[‡] Antti Rääke,^{||} Hjalmar Laudon,[¶] and Jussi Vuorenmaa^{||}



Increasing DOC concentrations in boreal freshwaters

- Interactive effects of climate, land use and acid deposition
- Increasing pool sizes (fertilization effect), mobilisation (reduced retention) and transport (increased precipitation)



Terrestrial greening and aquatic browning and light attenuation

LIMNOLOGY AND OCEANOGRAPHY
Letters

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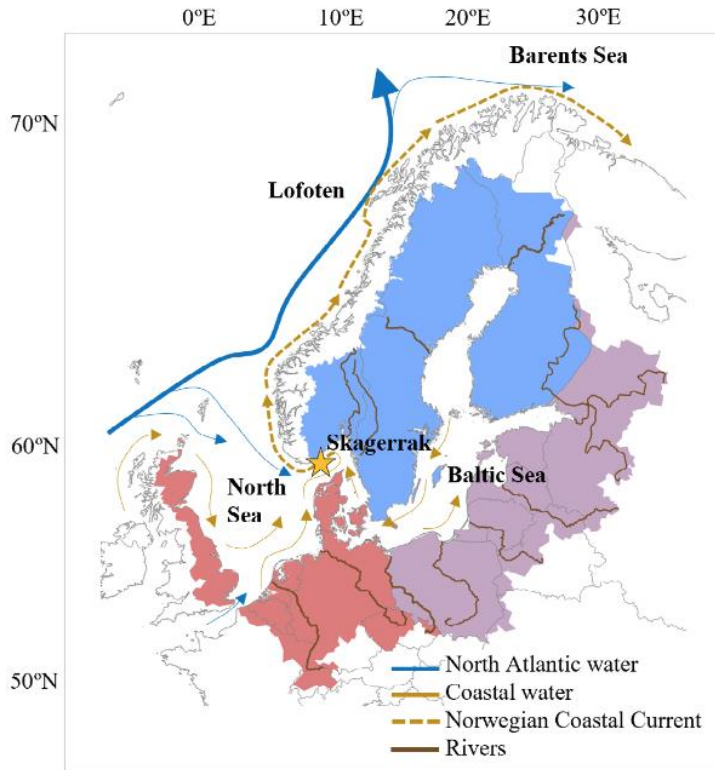
© 2023 The Authors. *Limnology and Oceanography Letters* published by Wiley Periodicals, LLC on behalf of Association for the Sciences of Limnology and Oceanography. doi: 10.1002/lol.10229

LETTER

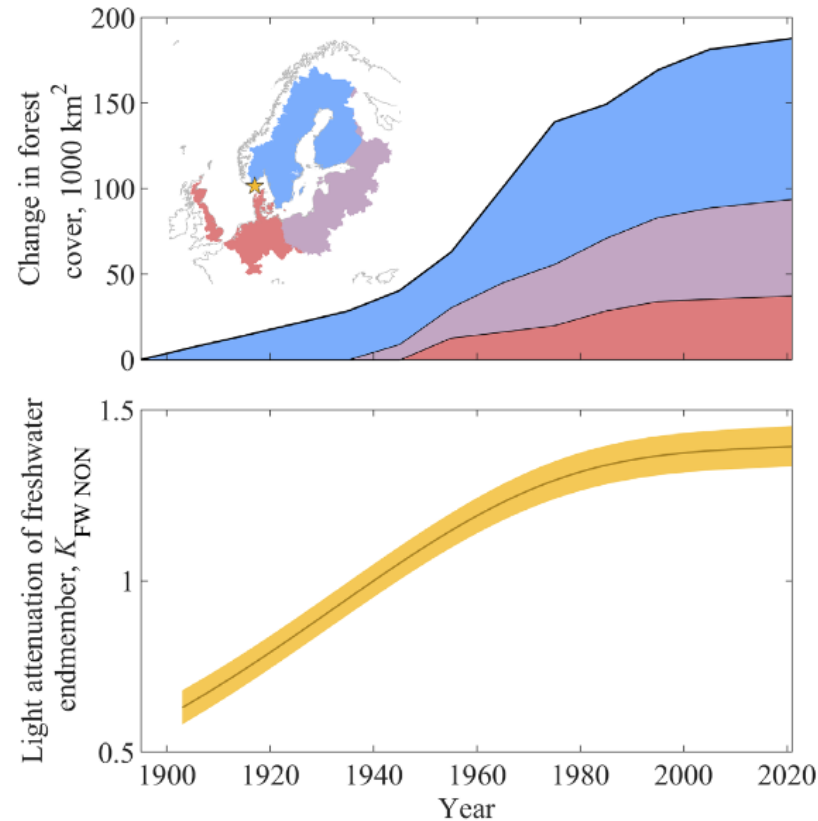
Tracking freshwater browning and coastal water darkening from boreal forests to the Arctic Ocean

Anders Frugård Opdal^{1,*}, Tom Andersen², Dag O. Hessen², Christian Lindemann¹, Dag L. Aksnes¹

¹Department of Biological Sciences, University of Bergen, Bergen, Norway; ²Department of Biosciences, University of Oslo, Oslo, Norway



Overview of drainage area, major rivers, water masses and currents. Drainage areas to the Skagerrak, Baltic Sea and North Sea are divided into Fennoscandia (blue), North-eastern Europe (purple), and North-western Europe (red).



- Increasing boreal forest cover
- Increasing light attenuation in the Skagerrak Sea
- Terrestrial greening and freshwater browning around the Baltic and North Sea has ramifications for coastal water clarity across thousands of kilometres
- Pointing toward an ecosystem connectivity from the Baltic lakes and forests to the Barents Sea.

Terrestrial greening, aquatic browning and ecosystem

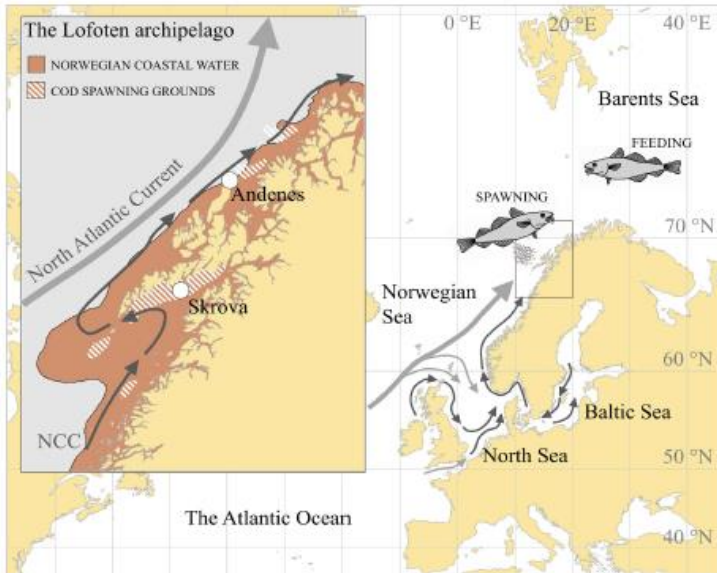
Received: 8 November 2023 | Revised: 21 March 2024 | Accepted: 18 April 2024
DOI: 10.1111/gcb.17308

RESEARCH ARTICLE

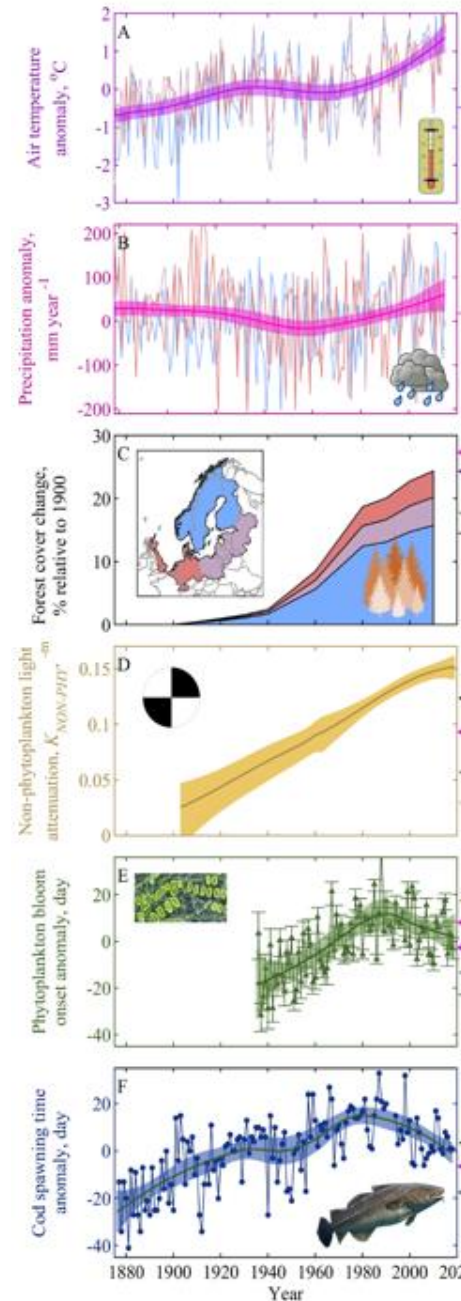
Global Change Biology WILEY

Land use change and coastal water darkening drive synchronous dynamics in phytoplankton and fish phenology on centennial timescales

Anders Frugård Opdal¹ | Christian Lindemann^{1,2} | Tom Andersen³ |
Dag O. Hessen³ | Øyvind Fiksen¹ | Dag L. Aksnes¹



Geographical overview of the Northeast Arctic cod feeding and spawning areas. The Northeast Arctic cod has its main feeding and nursery areas in the Barents Sea. In late autumn, mature cod migrate south to spawning grounds along the Norwegian coast. Spawning takes place between January and May. Eggs and later hatched larvae are carried by the northbound Norwegian Coastal Current (NCC) back to the Barents Sea. The insert shows the main spawning grounds (hatched) around the Lofoten archipelago



- Spatial connectivity between processes on land and in coastal waters
- Propagated through streams and rivers
- Ecosystems are connected into meta-ecosystem through the flow of energy and matter
- From ecosystem processes to population dynamics

Permafrost melt and river biogeochemistry



Permafrost melt and river biogeochemistry



Frozen Ground

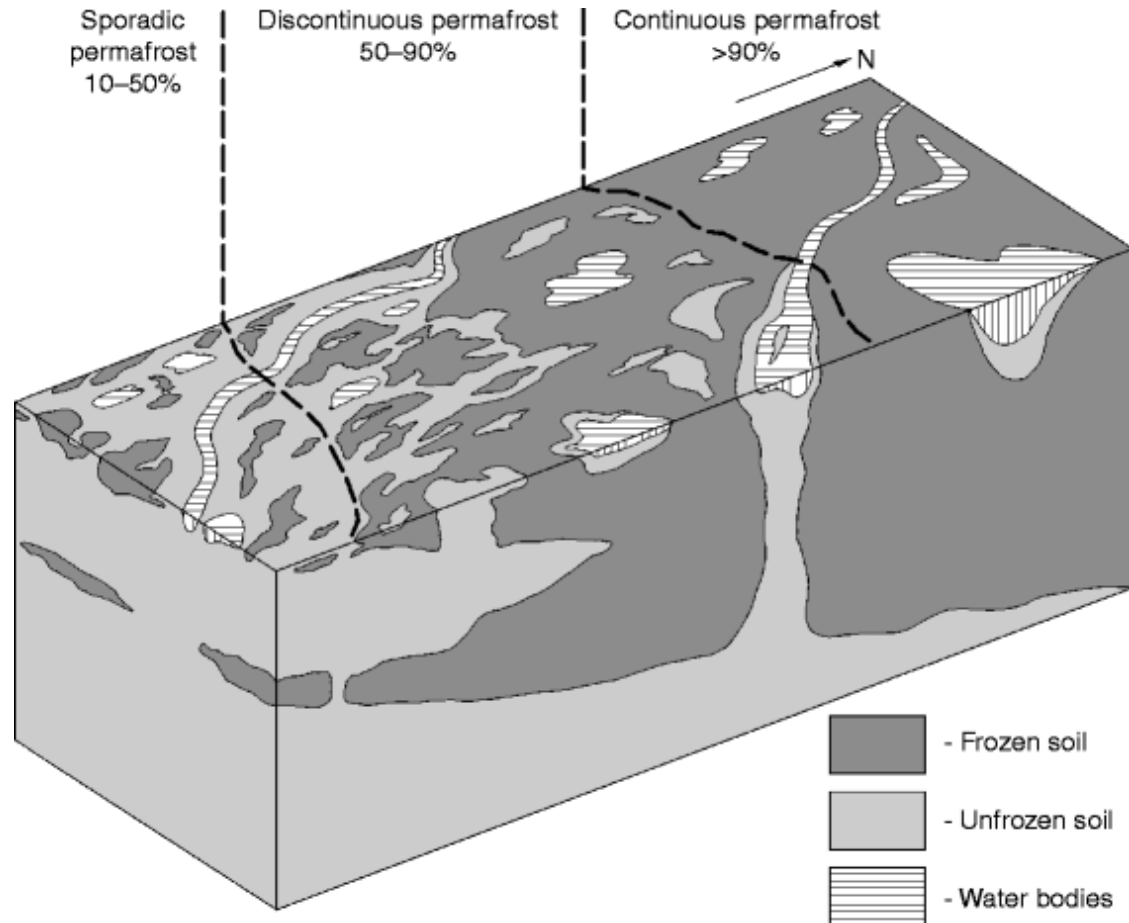
In the Northern Hemisphere, various types of permafrost cover about 9 million square miles, an area almost as large as the U.S., China and Canada combined. Global warming thaws the frozen soil, releasing climate-heating greenhouse gases.



SOURCE: International Permafrost Association, 1998

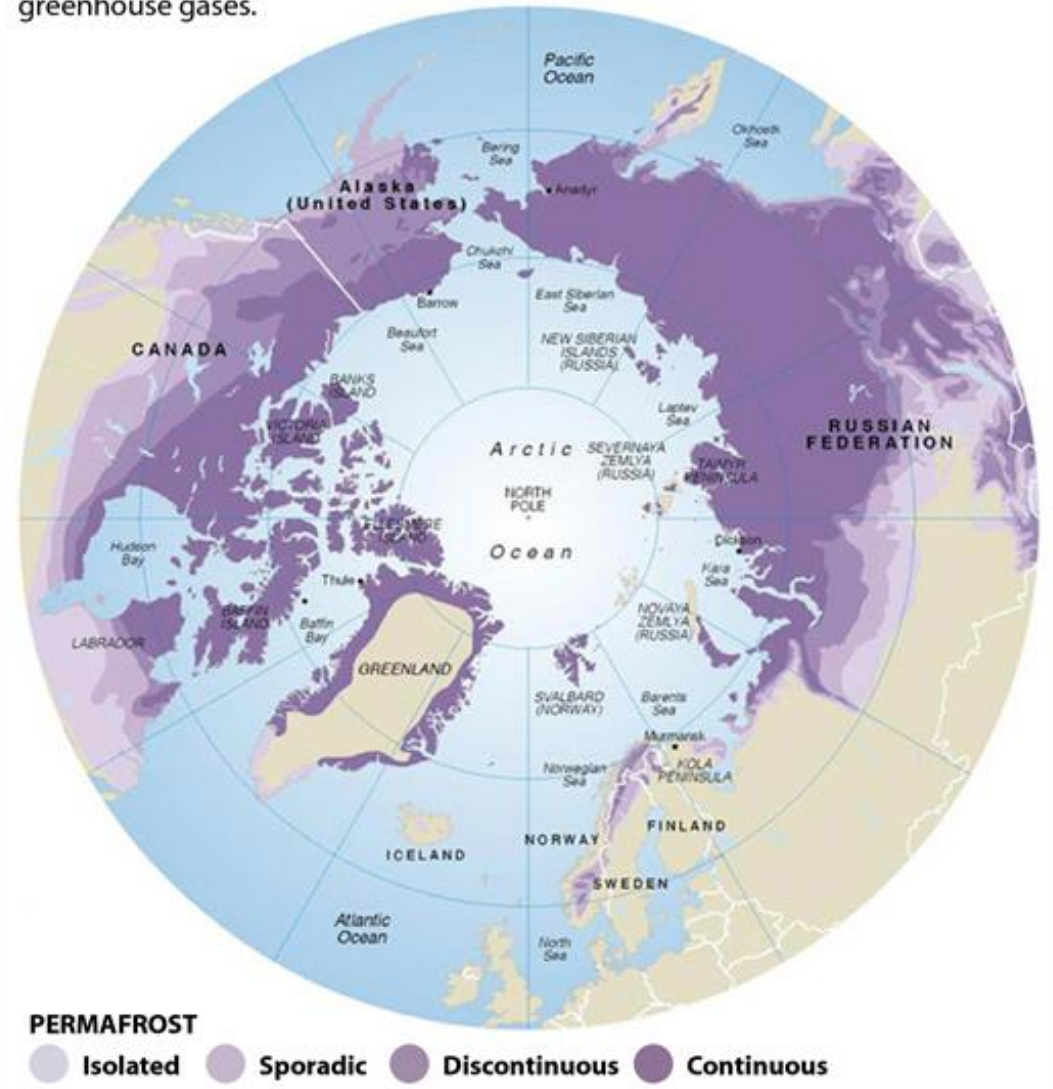
InsideClimate News

Permafrost melt and river biogeochemistry



Frozen Ground

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SOURCE: International Permafrost Association, 1998

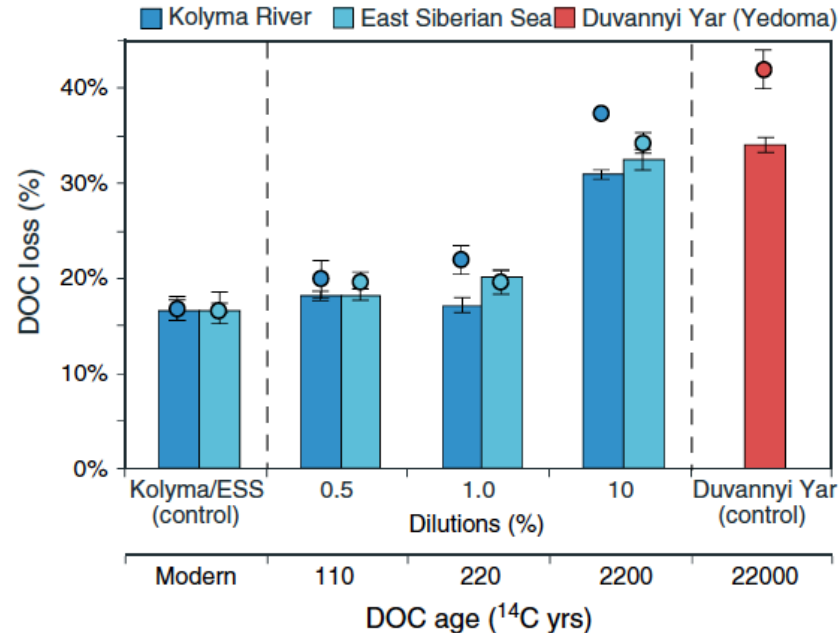
InsideClimate News

Permafrost organic carbon: old but highly

bioavailable

High biolability of ancient permafrost carbon upon thaw

Jorien E. Vonk,^{1,2,3} Paul J. Mann,⁴ Sergey Davydov,⁵ Anna Davydova,⁵
Robert G. M. Spencer,⁴ John Schade,⁶ William V. Sobczak,⁷ Nikita Zimov,⁵
Sergei Zimov,⁵ Ekaterina Bulygina,⁴ Timothy I. Eglinton,³ and Robert M. Holmes⁵



- Up to 41% of the DOC from Pleistocene Yedoma (up to 20 ky old) deposits bioavailable to the microbial metabolism
- High bioavailability when mixed with Kolyma River or East Siberian Sea water
- Permafrost organic carbon highly accessible to microbial respiration
- Relevance for greenhouse gas production with climate feedbacks

Figure 3. Dissolved organic carbon loss (%) after 14 days (bars) and 28 days (points) dark incubations at 20°C for Kolyma River (light blue), East Siberian Sea (dark blue), Yedoma streams (red), and three dilutions of Yedoma water with Kolyma River or East Siberian Sea water. The ¹⁴C age of DOC (years) (x-axis) represents the proportion of Duvannyi Yar (Yedoma) stream water added to Kolyma River or East Siberian Sea water. Standard deviations represent errors from triplicate experiments.

ENVIRONMENTAL STUDIES

Inland water greenhouse gas emissions offset the terrestrial carbon sink in the northern cryosphere

Chunlin Song^{1*†}, Shaoda Liu^{2†}, Genxu Wang^{1*†}, Liwei Zhang³, Judith A. Rosentreter⁴, Gang Zhao⁵, Xiangyang Sun¹, Yuanzhi Yao⁶, Cuihui Mu⁷, Shouqin Sun¹, Zhaoyong Hu¹, Shan Lin¹, Juying Sun¹, Yang Li¹, Ying Wang¹, Yuhao Li¹, Peter A. Raymond⁸, Jan Karlsson⁹

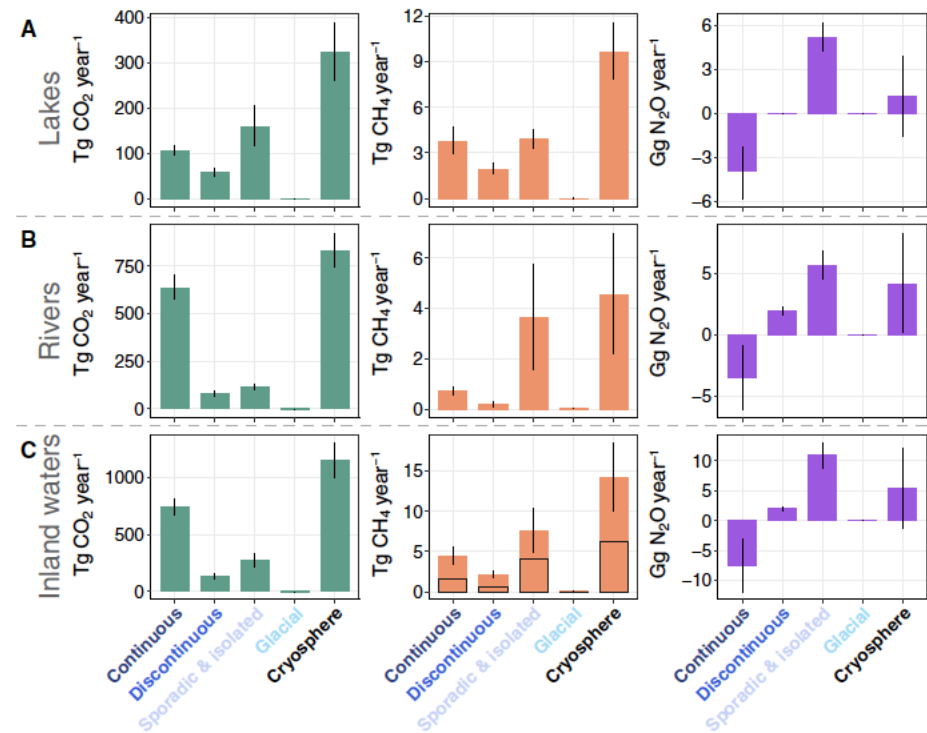
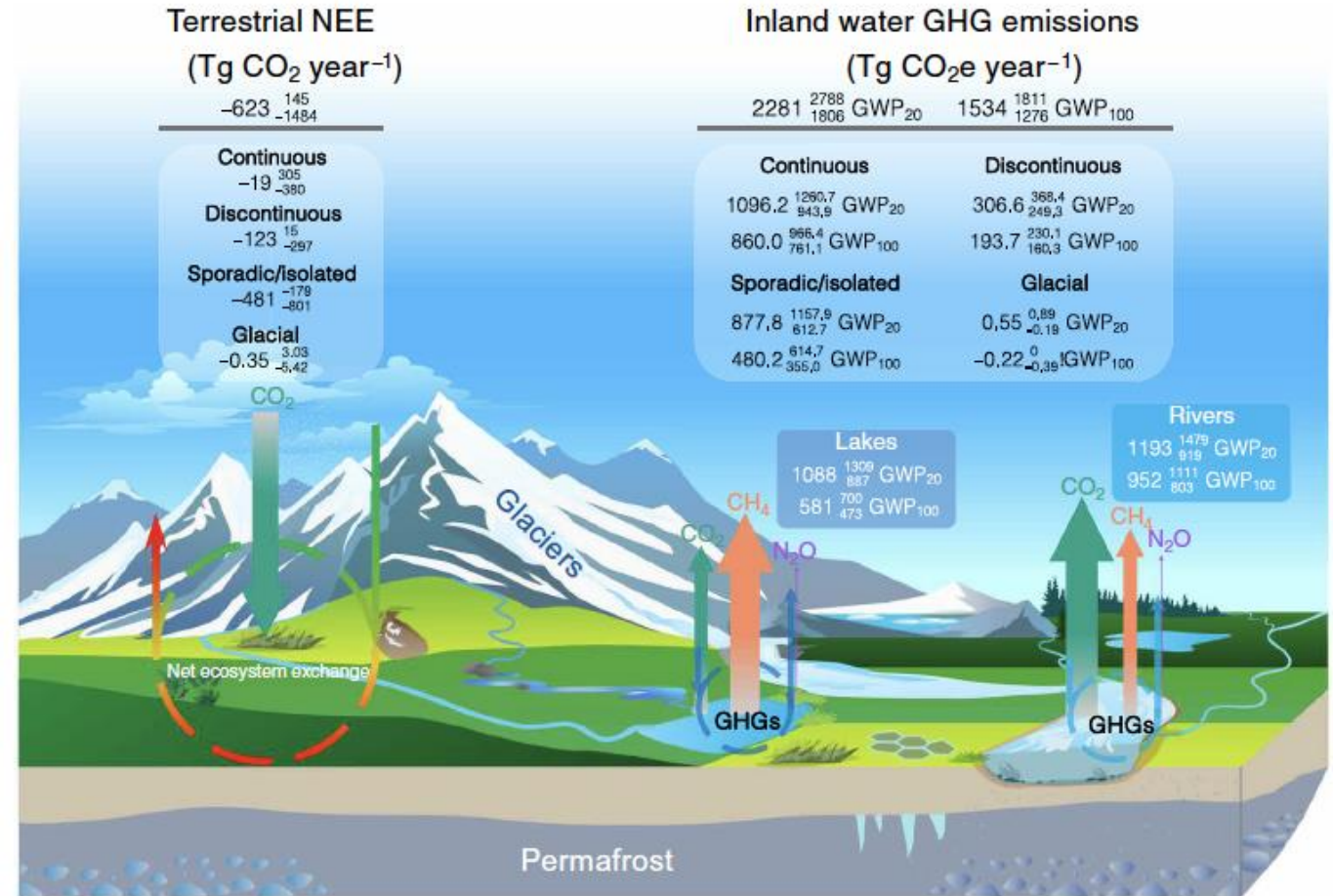


Fig. 3. Annual GHG emissions of northern cryosphere inland waters segregated by cryosphere zones. Barplots showing the (median, Q1 to Q3) annual GHG emissions in northern cryosphere (A) lakes, (B) rivers, and (C) inland waters (i.e., lakes and rivers combined). The black pillars in the CH₄ plots indicate the ebullition portions of the total CH₄ emissions.

- Larger CO₂ emissions from rivers than lakes
- Similar CH₄ emissions for rivers and lakes



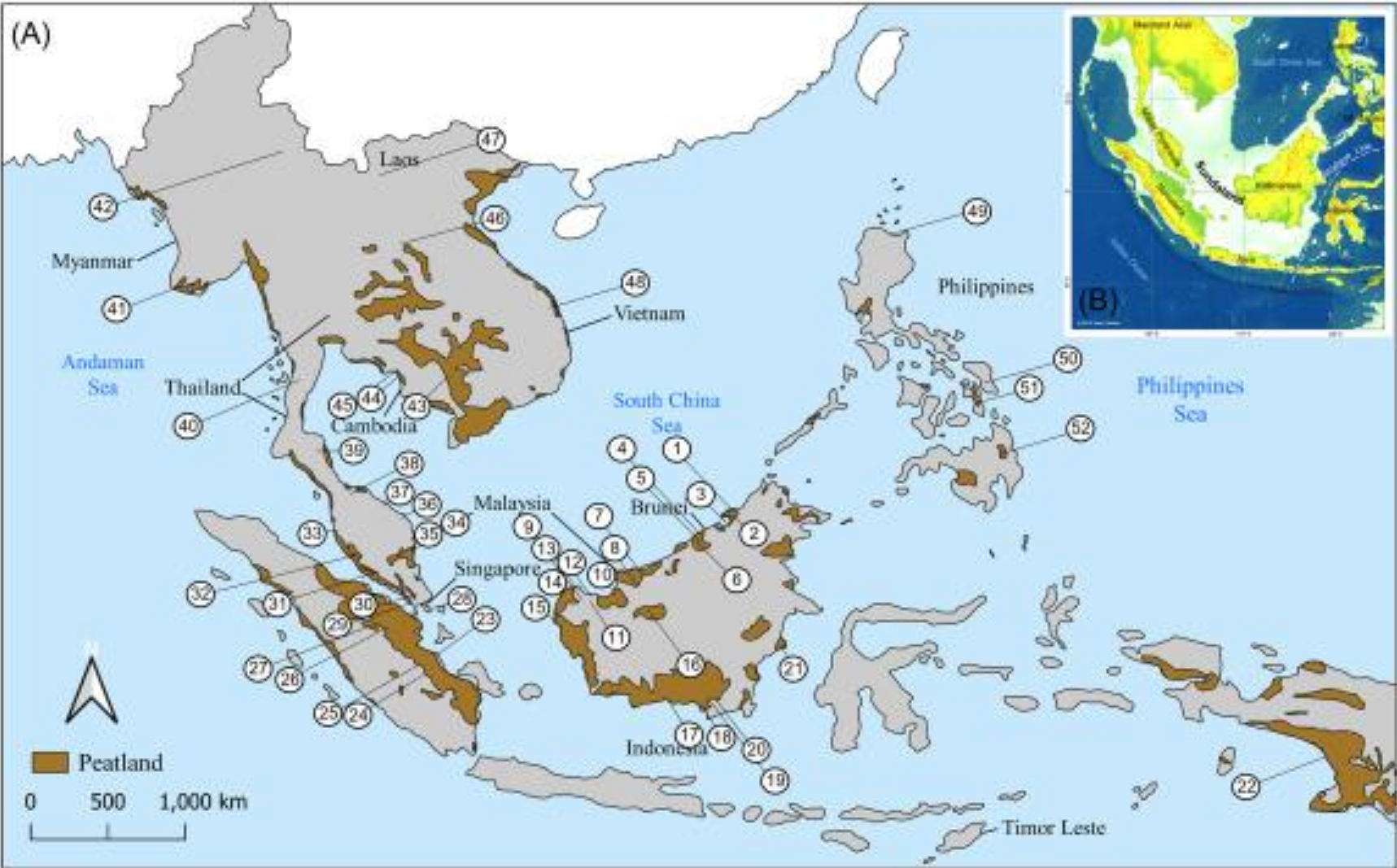
- Greenhouse gas emissions (as CO₂ equivalents) from rivers and lakes largely outpace terrestrial net ecosystem CO₂ exchange
- Underscores the role of inland waters for metabolism of permafrost organic matter and GHG production

Palm oil plantations in Southeast Asia and river and coastal biogeochemistry



Tropical peat in Southeast Asia

Tropical peatlands store around one-sixth of the global peatland carbon pool (that is 105 gigatonnes), equivalent to 30% of the carbon held in rainforest vegetation



Use of palm oil and plantations



<https://greenglobaltravel.com/how-to-avoid-products-with-palm-oil/>

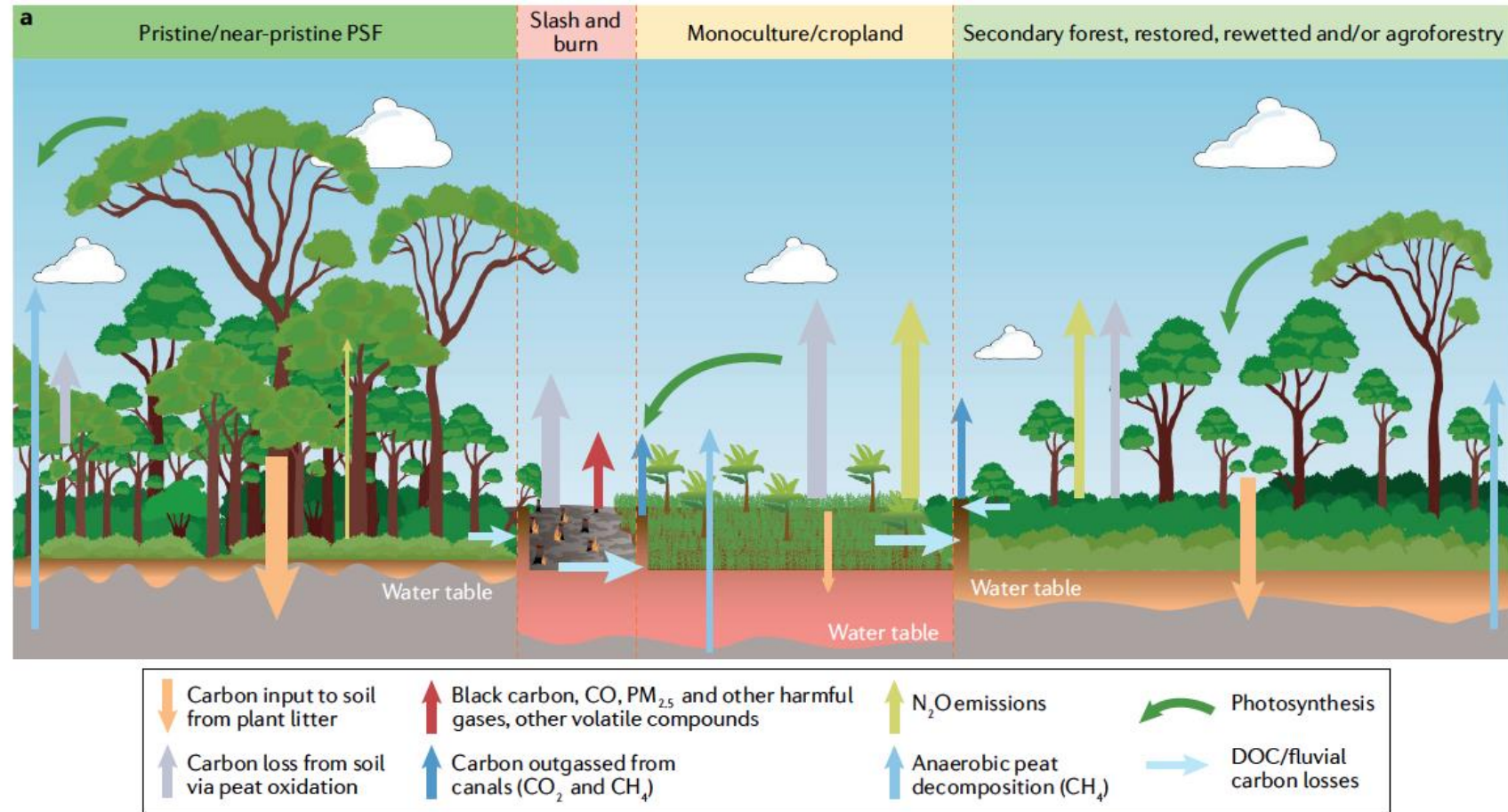


Anthropogenic impacts on lowland tropical peatland biogeochemistry

Susan Page¹, Shailendra Mishra², Fahmuddin Agus³, Gusti Anshari^{4,5}, Greta Dargie⁶, Stephanie Evers^{7,8}, Jyrki Jauhainen^{9,10}, Adi Jaya¹¹, Antonio Jonay Jovani-Sancho^{12,13}, Ari Laurén¹⁴, Sofie Sjögersten¹³, Ifo Averti Suspense¹⁵, Lahiru S. Wijedasa¹⁶ and Chris D. Evans¹²

- Drainage system, groundwater lowering and peat drying
- Prone to (wild)fires — CO₂ emissions
- Clear-cutting
- Loss of biodiversity
- Fundamental alterations of biogeochemical fluxes

Deterioration of tropic peatlands



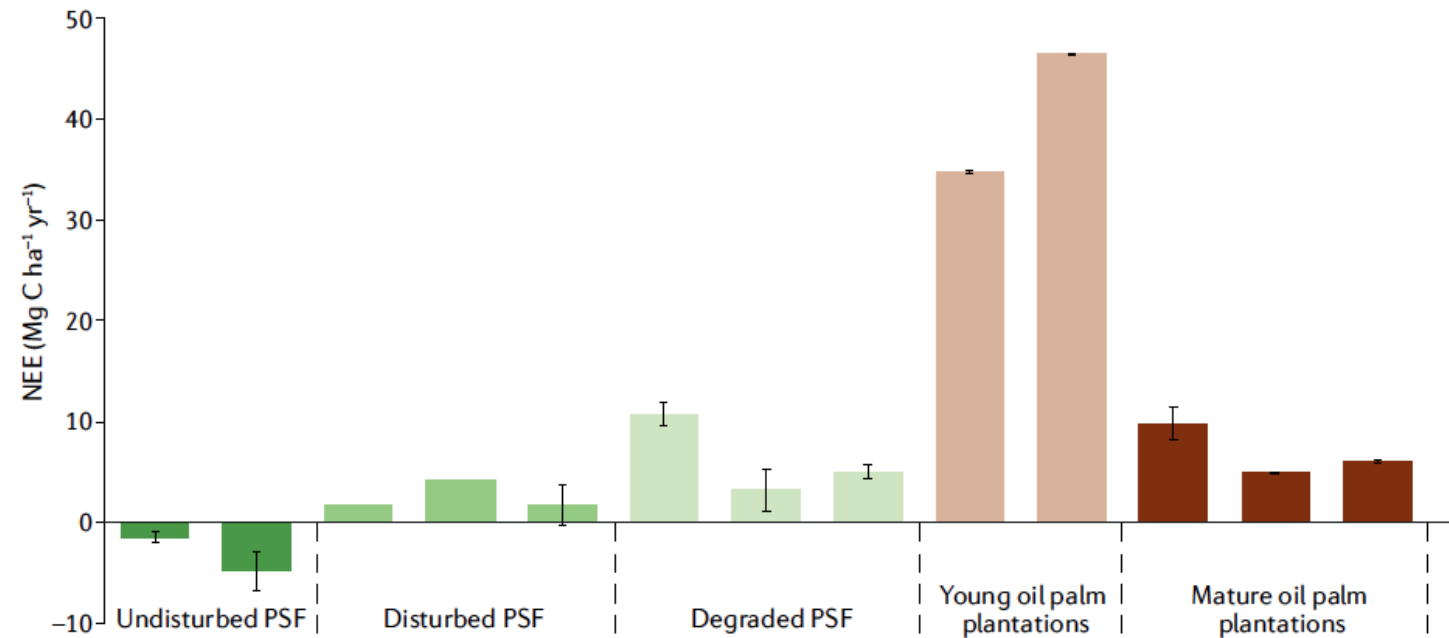


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- The conversion of native peat land to oil palm plantations inverses the ecosystem CO₂ exchange from a GHG sink to a source to the atmosphere
- Loss of soil organic carbon to stream networks....

Deterioration of tropical peatlands



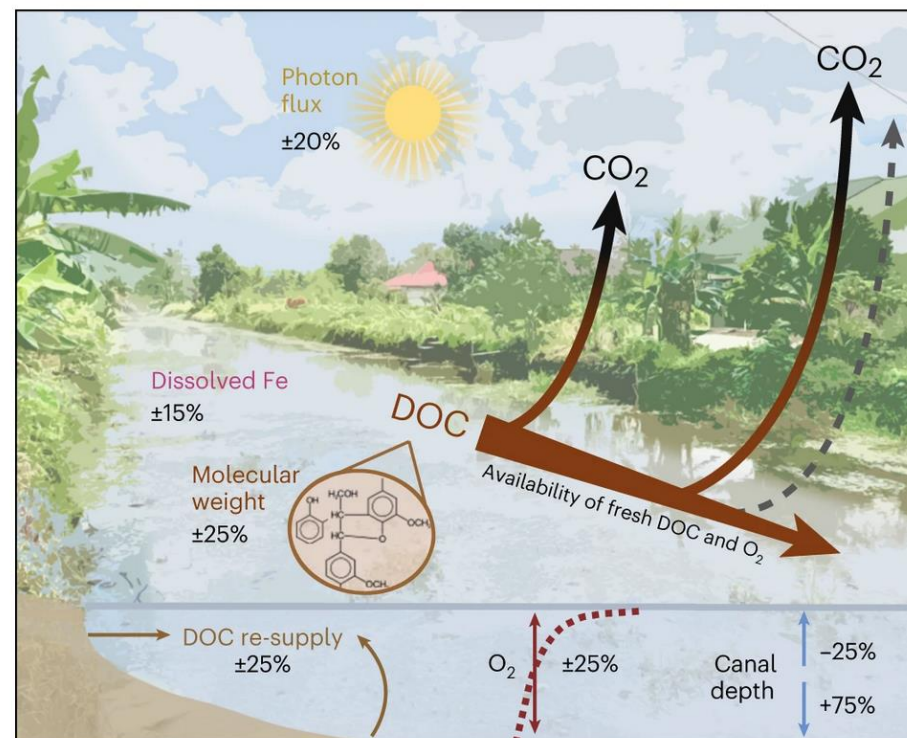
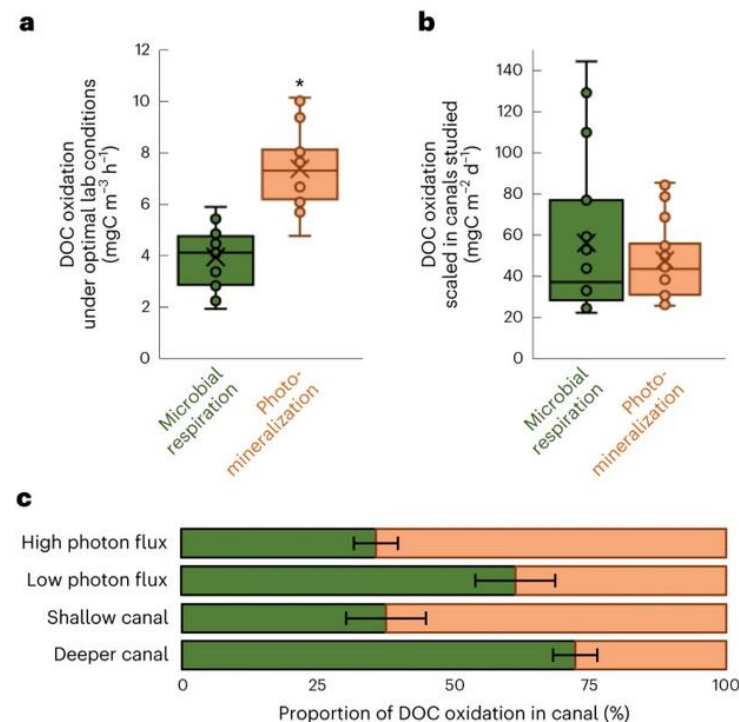
Peat Swamp Forest
Net Ecosystem Exchange

Canal networks regulate aquatic losses of carbon from degraded tropical peatlands

Received: 9 June 2023

Jennifer C. Bowen^{1,2}, Putri J. Wahyudjo³, Gusti Z. Anshari^{3,4},
Lihini I. Atuwihare¹ & Alison M. Hoyt²

Accepted: 25 January 2024



- The relative importance of microbial respiration and photomineralisation of DOC to CO_2 depends on solar radiation and channel depth (light attenuation)
- The concentration of dissolved iron present, the relative abundance of lower molecular-weight DOC compounds and dissolved O_2 (oxygenation, gas exchange) at deeper water depths, as well as DOC re-supply control DOC oxidation rates
- Iron-initiated photodecarboxylation of lignin-like compounds to CO_2 may be the primary mechanism for DOC photomineralization in the drainage canals. Photodecarboxylation involves the photochemical reduction of Fe^{III} to Fe^{II} , which initiates a ligand–metal charge-transfer reaction where a carboxyl group is oxidized to CO_2
- DOC/DOM that is not oxidized may be transported to the coastal waters

Rising dissolved organic carbon concentrations in coastal waters of northwestern Borneo related to tropical peatland conversion

Nivedita Sanwani^{1*†}, Chris D. Evans^{2,3,4}, Moritz Müller⁵, Nagur Cherukuru⁶, Patrick Martin^{1*}

Time series of satellite ocean color data from northwestern Borneo show that DOC concentrations in coastal waters have increased between 2002 and 2021 by $0.31 \mu\text{mol liter}^{-1} \text{ year}^{-1}$.

This was caused by a $\geq 30\%$ increase in the concentration of terrigenous DOC and coincided with the conversion of 69% of regional peatland area to non-forest land cover, suggesting that peatland conversion has substantially increased DOC fluxes to the sea.

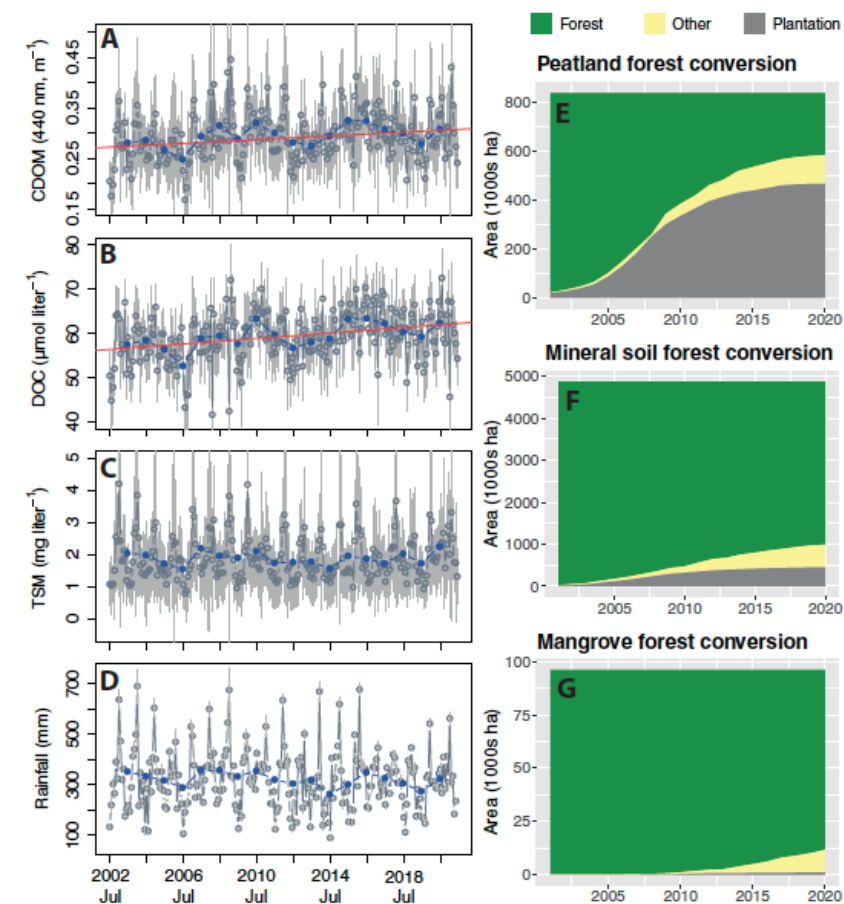


Fig. 3. Time series showing increased dissolved organic matter concentrations in coastal waters and land conversion of peatlands. Mean monthly (gray circles) and annual (blue dots) values of (A) CDOM absorption, (B) DOC concentration, (C) TSM concentration across the coastal waters, and (D) monthly precipitation on land. Solid red lines in (A) and (B) show statistically significant Theil-Sen trends ($P < 0.05$). The time series of TSM and rainfall showed no statistically significant trend. Gray error bars show 1 SD across the coastal water region (A to C) or across the land area (D). Land cover changes over time are shown for (E) peatlands, (F) mineral soil forest, and (G) mangrove forest.

OCEANOGRAPHY

Rising dissolved organic carbon concentrations in coastal waters of northwestern Borneo related to tropical peatland conversion

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Time series of satellite ocean color data from northwestern Borneo show that DOC concentrations in coastal waters have increased between 2002 and 2021 by $0.31 \mu\text{mol liter}^{-1} \text{year}^{-1}$.

This was caused by a $\geq 30\%$ increase in the concentration of terrigenous DOC and coincided with the conversion of 69% of regional peatland area to non-forest land cover, suggesting that peatland conversion has substantially increased DOC fluxes to the sea.

This rise in DOC concentration has also increased the underwater light absorption by dissolved organic matter, which may affect marine productivity by altering underwater light availability.

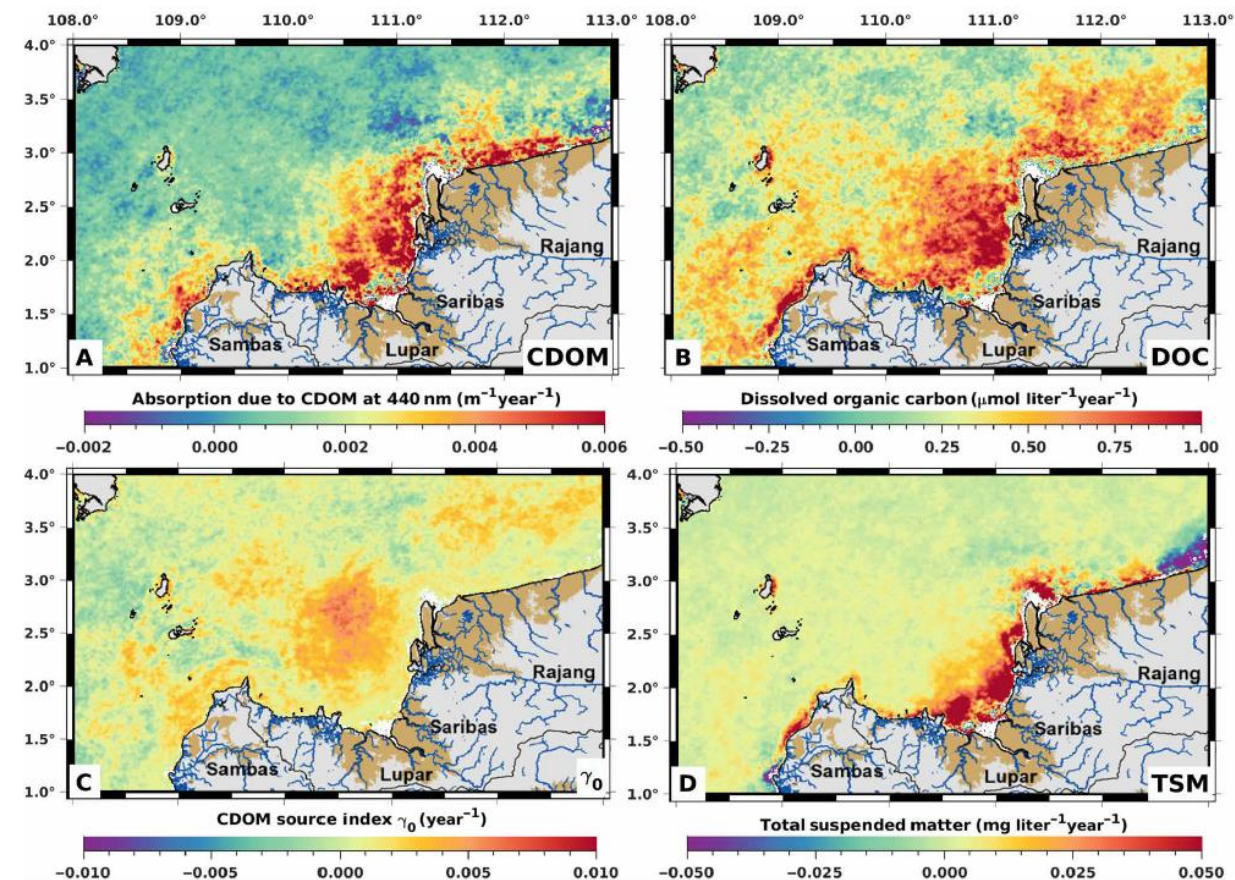


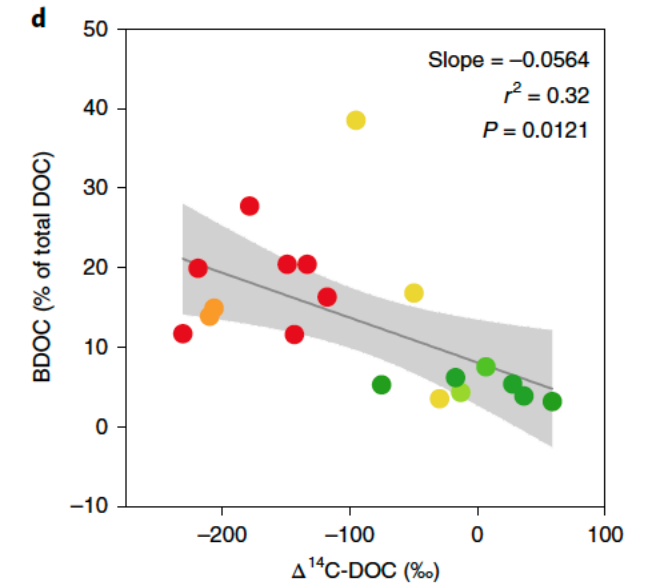
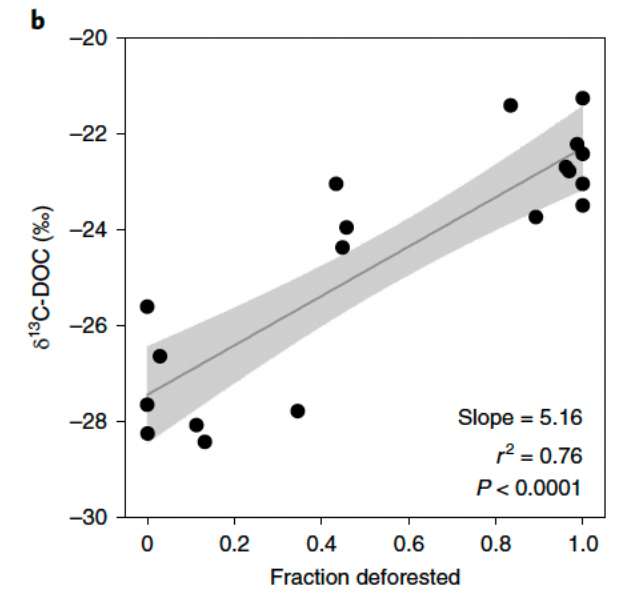
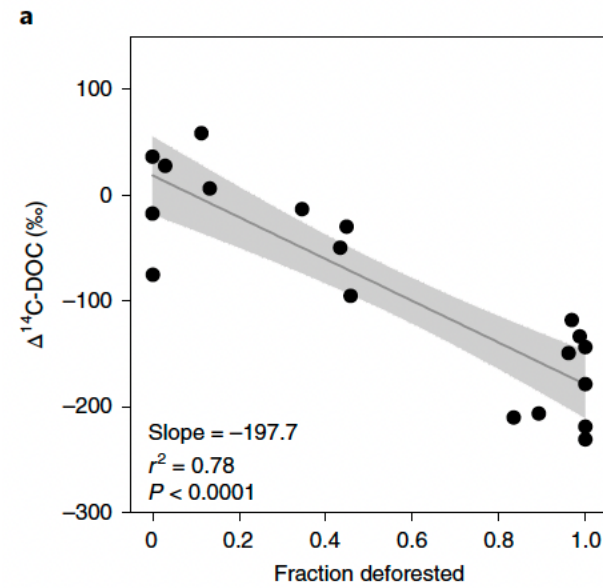
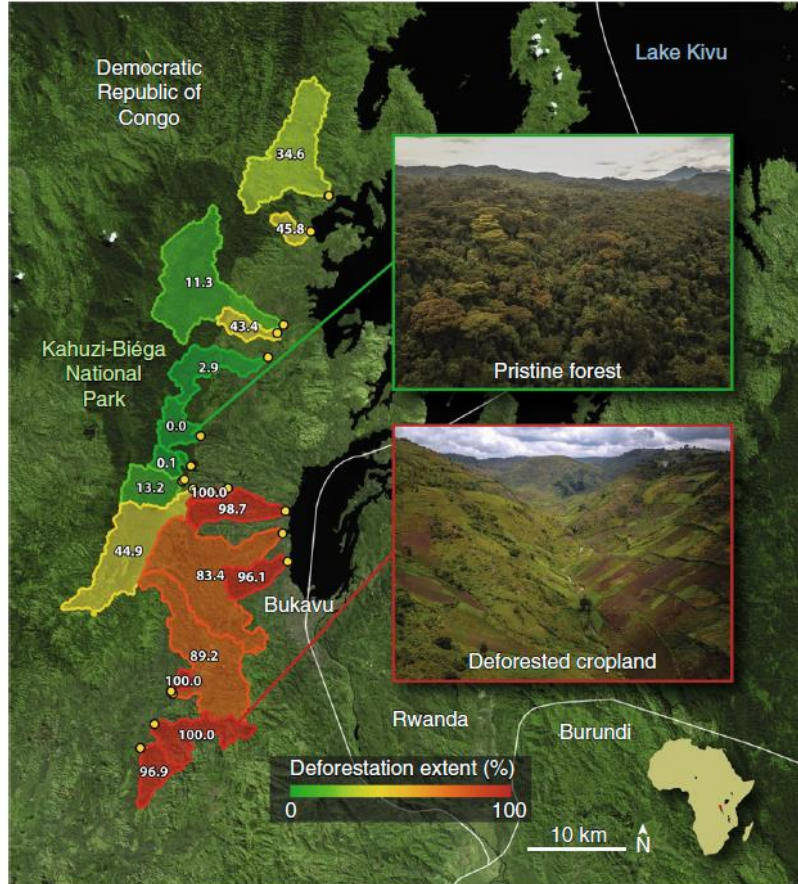
Fig. 4. Spatial distribution of trends in dissolved organic matter and TSM over the period 2002–2021. Theil-Sen trends were calculated for each 1-km^2 pixel across the time series for (A) CDOM, (B) DOC, (C) the CDOM source index γ_0 , and (D) TSM. The largest increasing trends in CDOM and DOC occurred in coastal waters adjacent to the main peatland areas (A and B), while for TSM, only small and inconsistent (positive and negative) trends were seen across the region (D). Trends in γ_0 are greater somewhat further from shore, reflecting the fact that γ_0 close to shore is already high due to the dominance of terrigenous DOC in these waters throughout the time series (cf. Fig. 1) and the fact that spectral slopes show nonlinear concentration-dependent changes (see Methods).

Deforestation in Africa



Mobilization of aged and biolabile soil carbon by tropical deforestation

Travis W. Drake^{1,2,11*}, Kristof Van Oost³, Matti Barthel⁴, Marijn Bauters^{5,6}, Alison M. Hoyt^{7,8}, David C. Podgorski^{1,2,12}, Johan Six⁴, Pascal Boeckx⁵, Susan E. Trumbore^{7,9}, Landry Cizungu Ntaboba¹⁰ and Robert G. M. Spencer^{1,2}



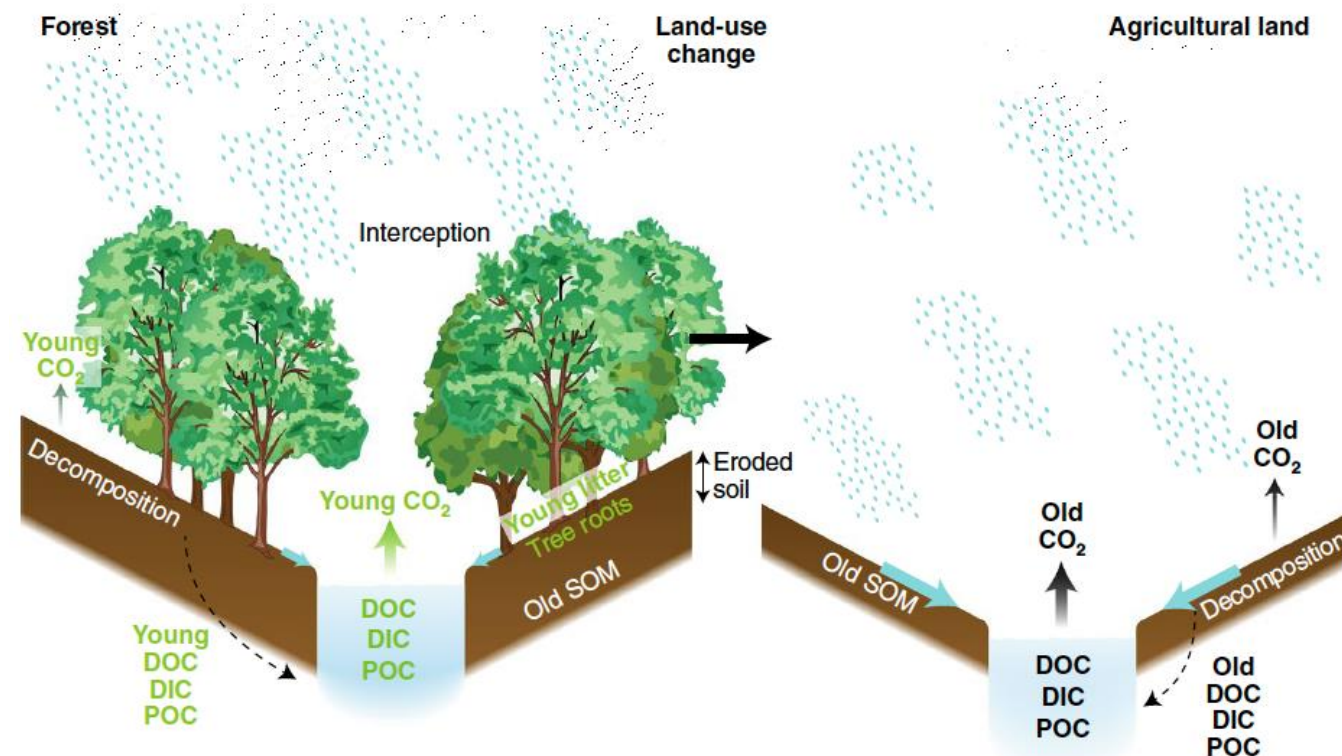
- Deforestation mobilized old and soil-derived DOC to the streams
- Old terrigenous DOC is highly bioavailable to the microbial metabolism

Mobilization of aged and biolabile soil carbon by tropical deforestation

Travis W. Drake^{1,2,11*}, Kristof Van Oost³, Matti Barthel⁴, Marijn Bauters^{5,6}, Alison M. Hoyt^{7,8}, David C. Podgorski^{1,2,12}, Johan Six⁴, Pascal Boeckx⁵, Susan E. Trumbore^{7,9}, Landry Cizungu Ntaboba¹⁰ and Robert G. M. Spencer^{1,2}

Pristine forests protect deeper and old SOM from erosion. OM from young primary production is metabolised on land or transported via surface and shallow runoff to streams. In streams, this OM is slowly decomposed with the production of young CO₂.

Removal of trees exposes soils to heavy rain (tropics!), which increases the rate of surface run-off and soil erosion. SOM from those soils increasingly flows into rivers where it is rapidly degraded with the production of old CO₂.



Old carbon routed from land to the atmosphere by global river systems

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A new model for old carbon

- Old organic carbon fuels the contemporary metabolism in streams and rivers
- Gaining importance as old stores are being mobilized

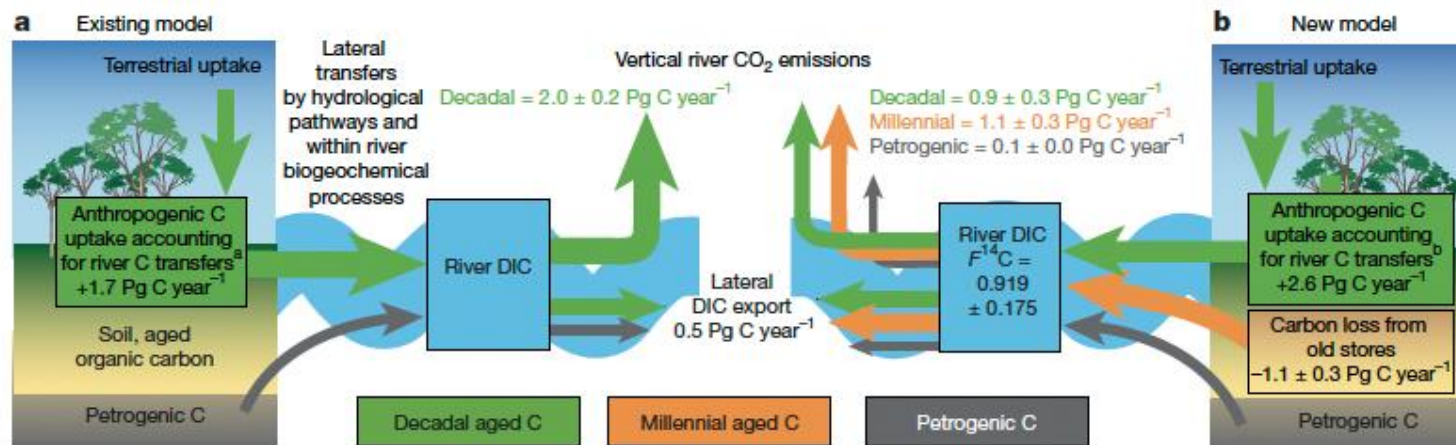
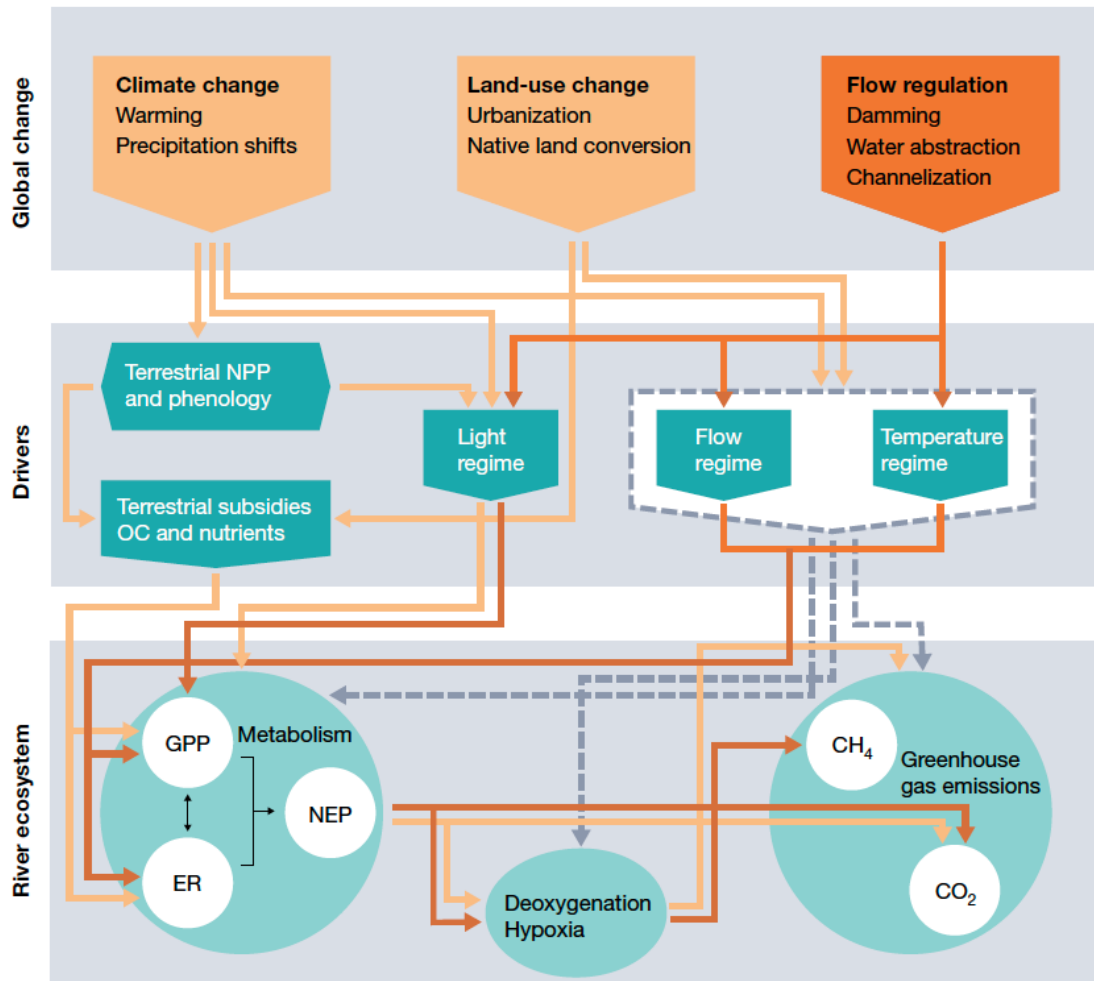


Fig. 3 | The importance of river CO₂ emission age for the global carbon cycle. **a**, Existing model in which river CO₂ is only derived from young, rapid-cycling carbon (decadal-aged = green); lateral DIC export to the coast is considered a mixture of decadal and petrogenic inputs (grey). By accounting for these river carbon losses, it is estimated that 1.7 Pg C year⁻¹ of anthropogenic carbon emitted to the atmosphere may be accumulating in the rapid-cycling terrestrial carbon pools³; ^anote that this estimate is based on a lower estimate of vertical river CO₂ emissions of 1.51 Pg C year⁻¹. **b**, Revised conceptual model based on

the assembled F¹⁴C values of river DIC, CO₂ and CH₄ presented here; millennial carbon inputs are needed from organic matter degradation in soils or river sediments (orange) as well as petrogenic carbon from rock weathering to explain the observed F¹⁴C values in our database. This revised conceptual model indicates a loss of carbon from an old (millennial) store on land through vertical river CO₂ emissions; a first-order estimate of the impact on the partitioning of carbon in the biosphere and soils is provided (^b).



Land use change

- Climate change (temperature, CO₂ fertilization, precipitation)
- Native land conversion

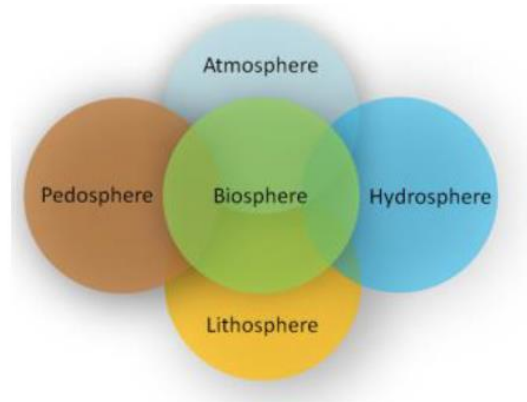
Changes in flow regimes

- Increased hydrological connectivity (land-river-coastal waters)

Terrestrial primary production

- Terrestrial subsidies of organic matter (and nutrients...)
- Stores of old organic matter become mobilized
- Fuel contemporary aquatic metabolism
- Contribution to GHG emissions with potential climate feedbacks

A better appreciation of biogeochemistry



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 primary production, respiration, decomposition, weathering, erosion, and sedimentation.

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

