

River Biogeochemistry

A teaser

Tom J. Battin

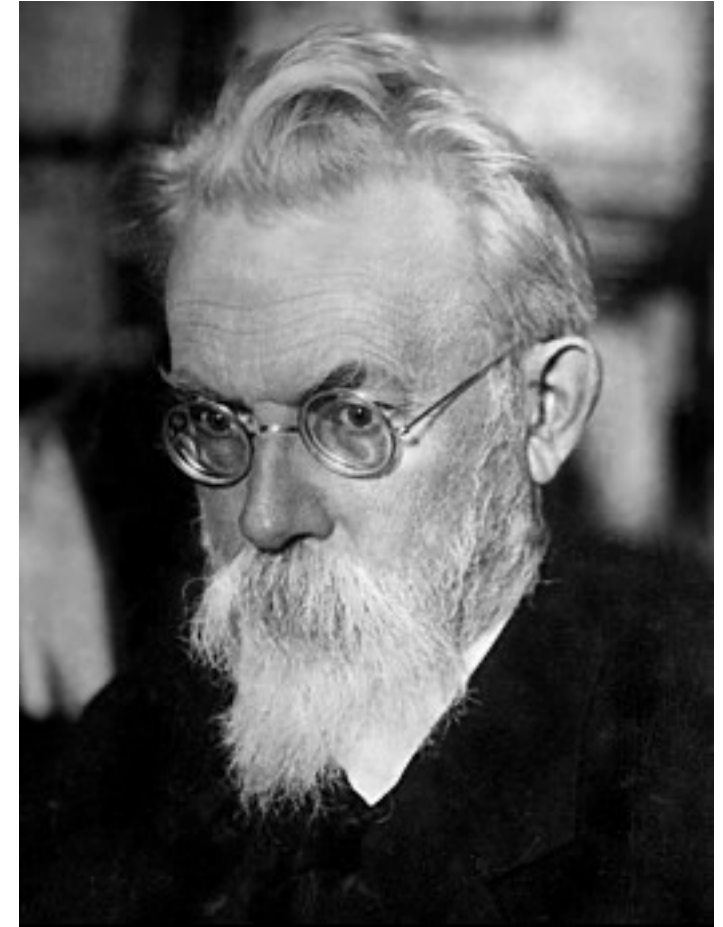
EPFL River Ecosystems Laboratory

Biogeochemistry is the scientific discipline that studies the physical, chemical and biological processes that govern the composition and health of the natural environment

William Schlesinger

“the chemistry of the arena of life— that is Earth’s biogeochemistry— will be at the center of how well we do, and all biogeochemists should strive to articulate that message clearly and forcefully to the public and to leaders of society, who must know our message to do their job well.”

“... the premier scientific discipline to examine human impacts on the global environment.”



Vladimir Vernadsky

Biogeochemistry and ecosystem science are inherently linked by the study of the flow of energy and nutrients.

They strive to understand basic mechanistic processes at scales from within ecosystems to the entire globe and provide a framework for investigating aspects of global change



Rivers

- Natural channels configured to ensure transportation of water and sediments
- Flood events (current: warm Mediterranean, impermeabilisation, channelisation)

Perception of hydrologists long shaped our understanding of rivers as ‘pipelines’

[Physical transport overwhelms biogeochemical transformations]



The superlatives of rivers

Largest biogeochemical nexus between land, the oceans and atmosphere

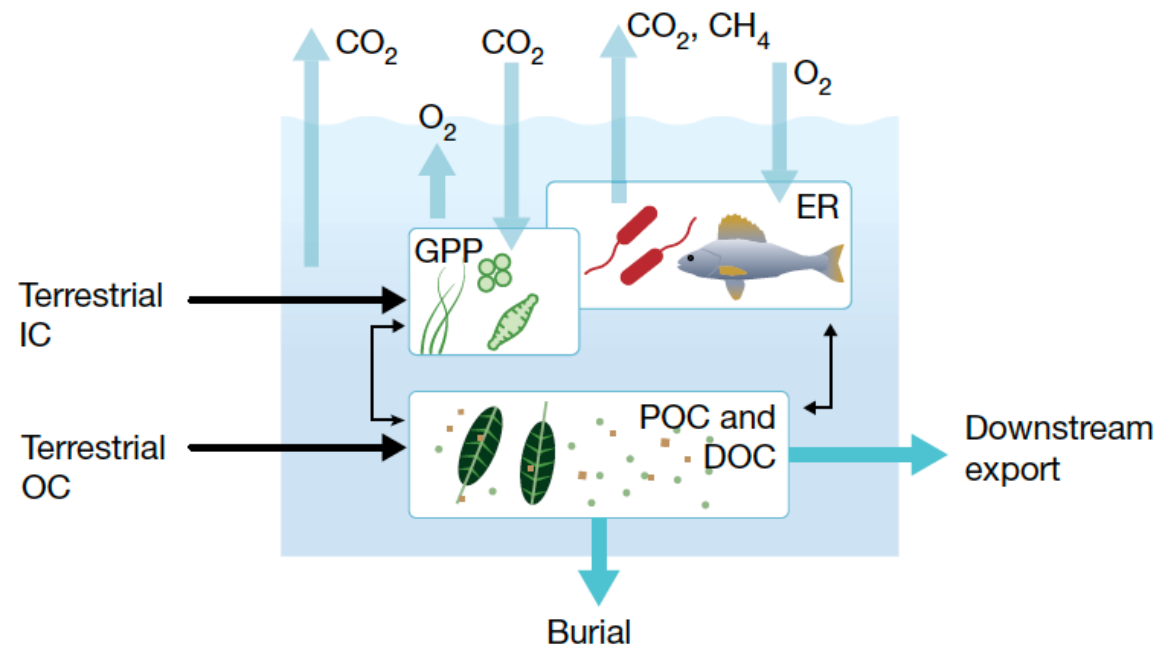
Span multiple catchments and biomes

High biodiversity

Provide critical ecosystem services (e.g., drinking water, proteins, hydropower)



Largest biogeochemical nexus between land, the oceans and atmosphere



River ecosystem metabolism

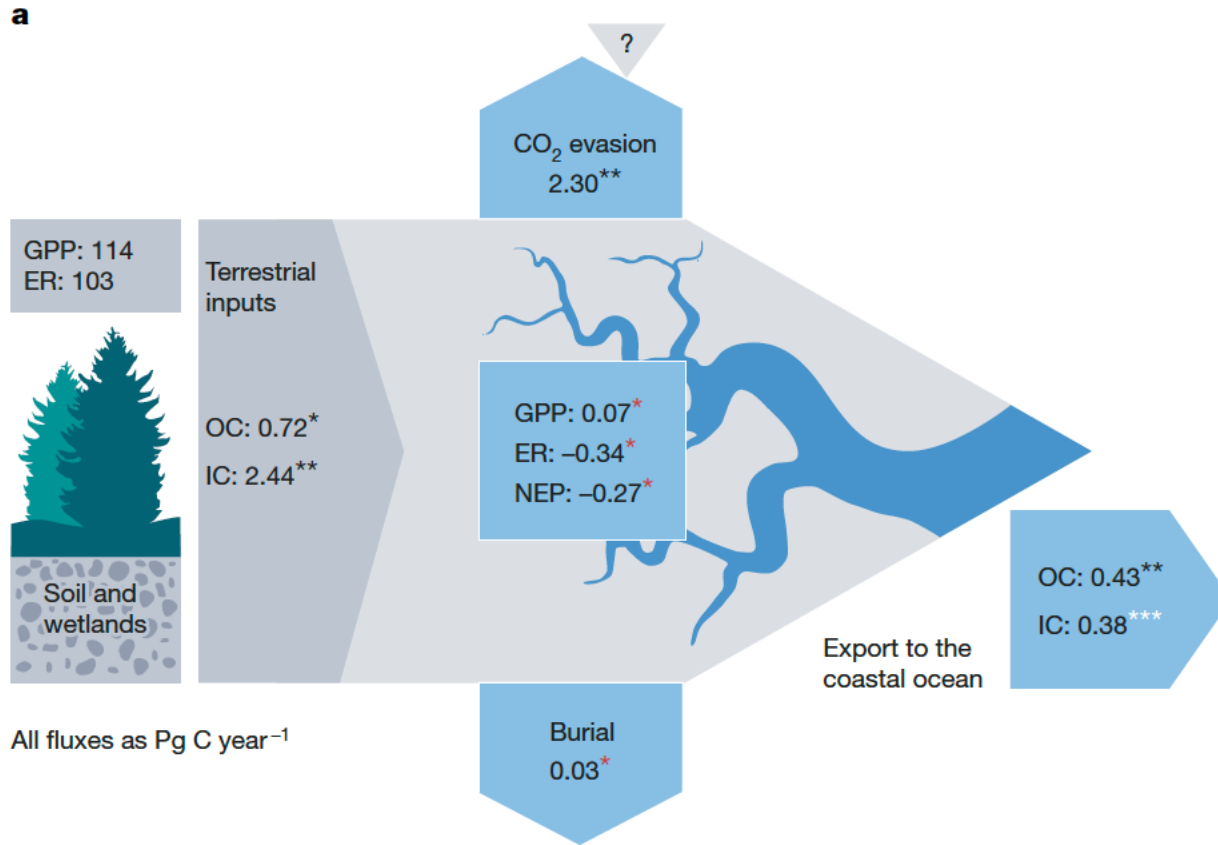
Respiration and Gross Primary Production

- Sum of metabolic activities of all organisms
- Controls carbon and nutrient cycling
- Regulates greenhouse (CO₂, CH₄) production

Metabolism = ecosystem process

Carbon and nutrient cycling = biogeochemical process

Largest biogeochemical nexus between land, the oceans and atmosphere



1 Gigatonne (Gt) = 1 billion tonnes = 1×10^{15} g = 1 Petagram (Pg)

- Rivers figure among the most heterotrophic ecosystems (that is, they respire more than they produce)
- The world's rivers are major CO₂ sources to the atmosphere [...this is a natural process]
- They receive OC from the terrestrial primary production, which they respire, store or transport downstream
- They receive CO₂ from terrestrial respiration and rock weathering, which they outgas to the atmosphere
- These processes shift the ratio of organic-to-inorganic carbon en route from small streams to the coastal ocean

The world's rivers are now part of the IPCC Global Carbon Budget

Chapter 5

Global Carbon and Other Biogeochemical Cycles and Feedbacks

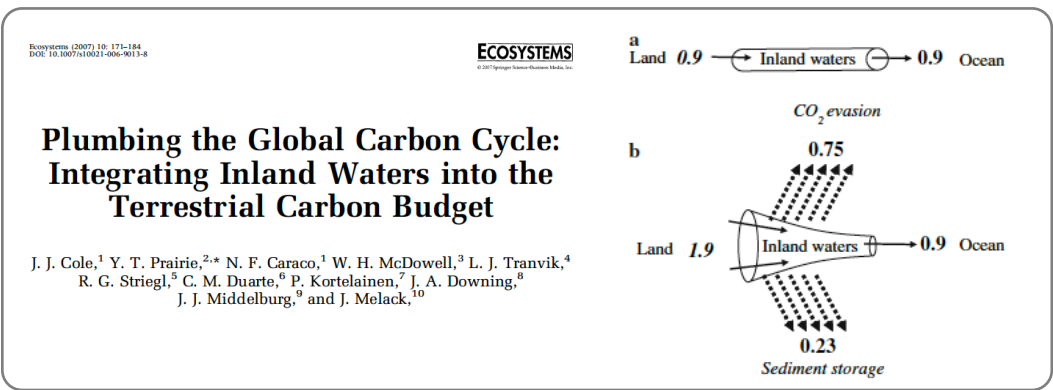
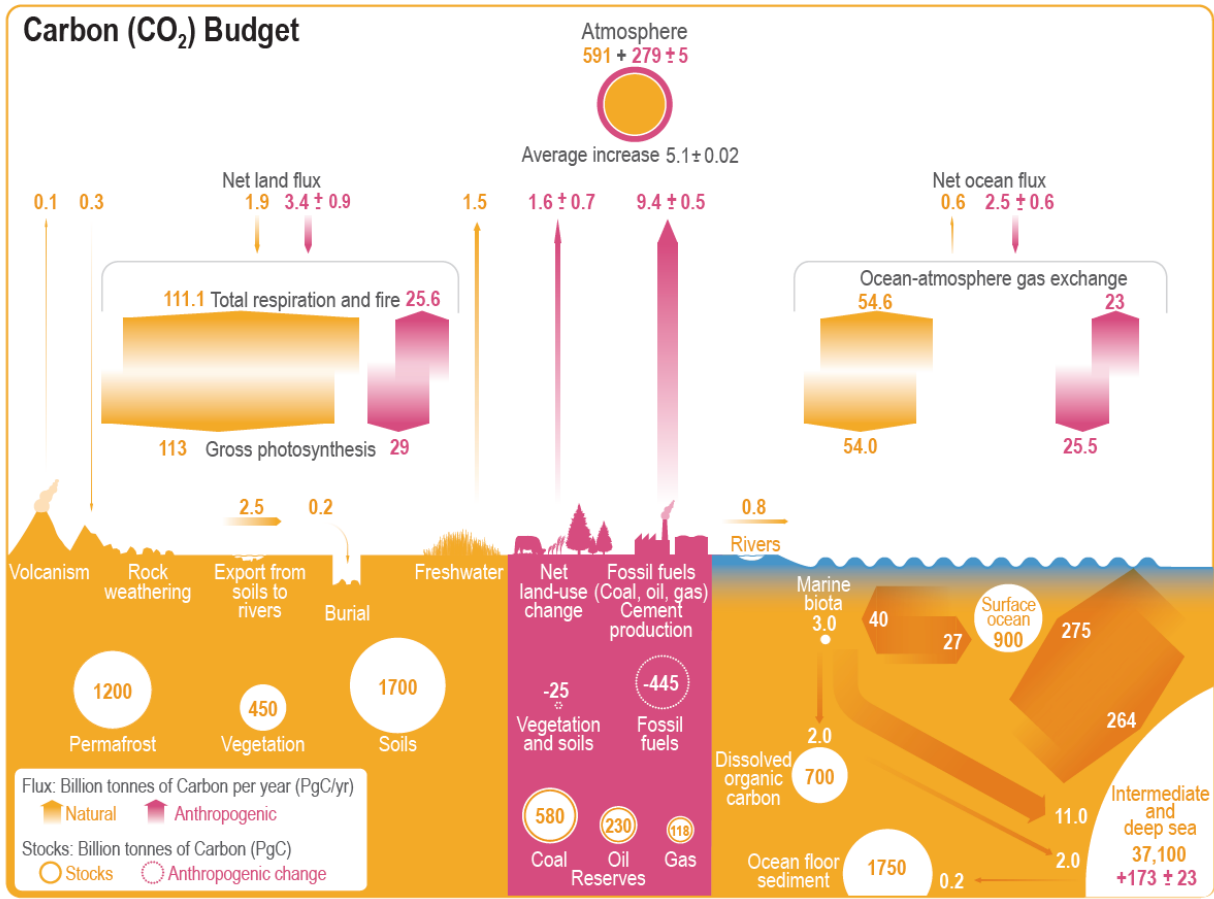
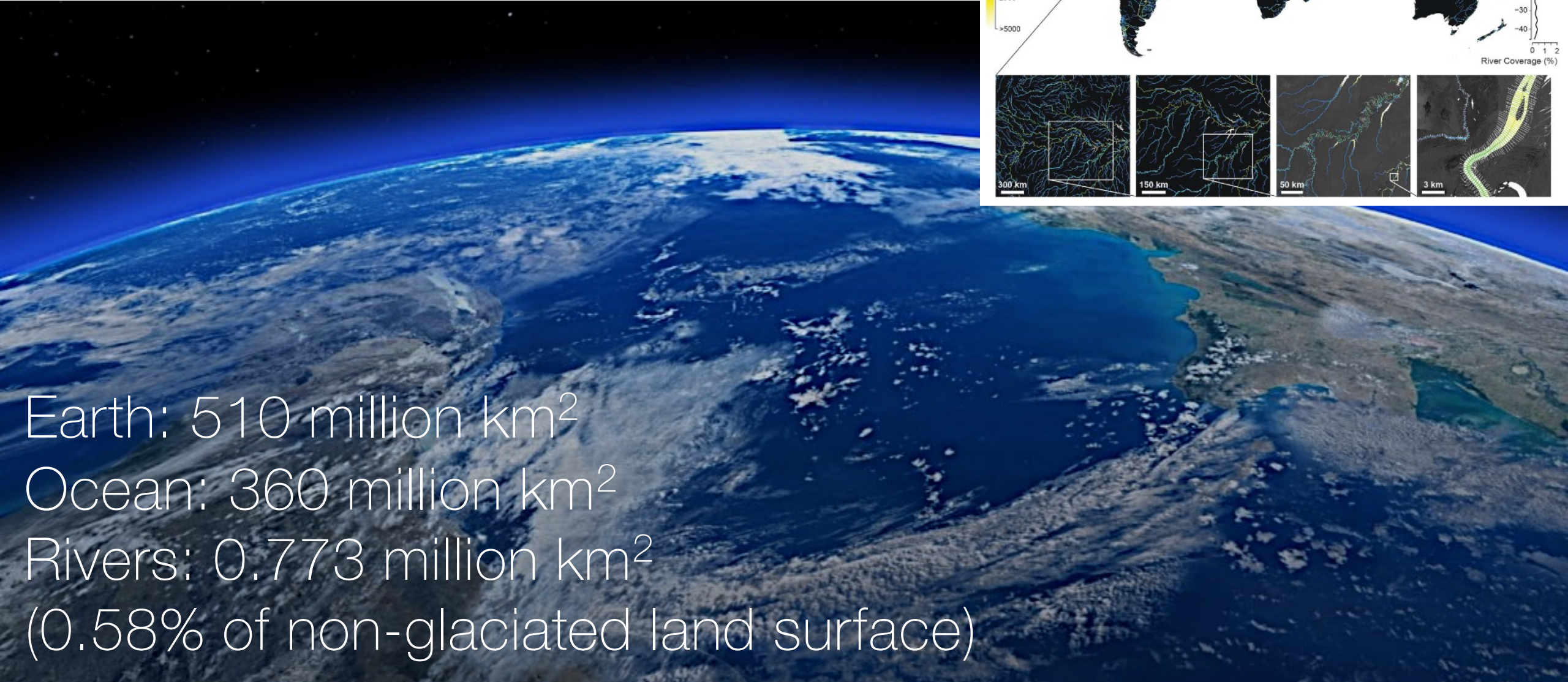
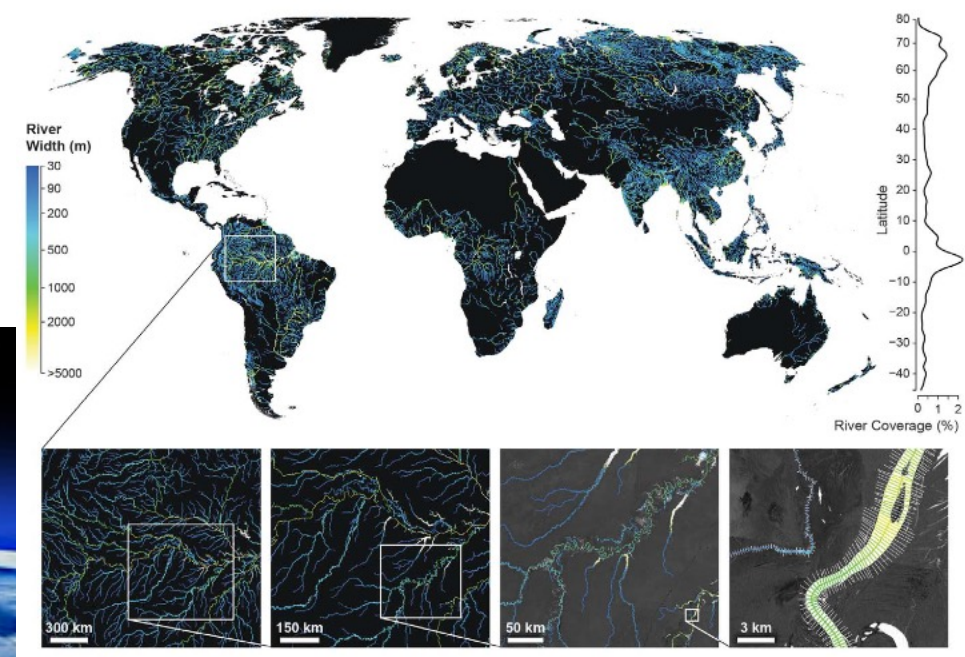


Figure 5.12 | Global carbon (CO₂) budget (2010–2019). Yellow arrows represent annual carbon fluxes (in PgC yr⁻¹) associated with the natural carbon cycle, estimated for the time prior to the industrial era, around 1750. Pink arrows represent anthropogenic fluxes averaged over the period 2010–2019. The rate of carbon accumulation in the atmosphere is equal to net land-use change emissions, including land management (called LULUCF in the main text) plus fossil fuel emissions, minus land and ocean net sinks (plus a small budget imbalance, Table 5.1). Circles with yellow numbers represent pre-industrial carbon stocks in PgC. Circles with pink numbers represent anthropogenic changes to these stocks (cumulative anthropogenic fluxes) since 1750. Anthropogenic net fluxes are reproduced from Friedlingstein et al. (2020). The relative change of gross photosynthesis since pre-industrial times is based on 15 DGVMs used in Friedlingstein et al. (2020). The corresponding emissions by total respiration and fire are those required to match the net land flux, exclusive of net land-use change emissions which are accounted for separately. The cumulative change of anthropogenic carbon in the terrestrial reservoir is the sum of carbon cumulatively lost by net land-use change emissions, and net carbon accumulated since 1750 in response to environmental drivers (warming, rising CO₂, nitrogen deposition). The adjusted gross natural ocean–atmosphere CO₂ flux was derived by rescaling the value in Figure 1 of Sarmiento and Gruber (2002) of 70 PgC yr⁻¹ by the revised estimate of the bomb radiocarbon (¹⁴C) inventory in the ocean. The original bomb ¹⁴C inventory yielded an average global gas transfer velocity of 22 cm hr⁻¹; the revised estimate is 17 cm hr⁻¹ leading to 17/22*70=54. Dissolved organic carbon reservoir and fluxes from Hansell et al. (2009). Dissolved inorganic carbon exchanges between surface and deep ocean, subduction and obduction from Levy et al. (2013). Export production and flux from (Boyd et al., 2019). Net primary production (NPP) and remineralization in surface layer of the ocean from Kwiatkowski et al. (2020); Séférian et al. (2020). Deep ocean reservoir from Keppler et al. (2020). Anthropogenic carbon reservoir in the ocean is from Gruber et al. (2019b) extrapolated to 2015. Fossil fuel reserves are from BGR (2020); fossil fuel resources are 11,490 PgC for coal, 6,780 PgC for oil and 365 PgC for natural gas. Permafrost region stores are from Hugelius et al. (2014); Strauss et al. (2017); Mishra et al. (2021) (see also Box 5.1) and soil carbon stocks outside of permafrost region from Batjes (2016); Jackson et al. (2017). Biomass stocks (range of seven estimates) are from Erb et al. (2018). Sources for the fluxes of the land–ocean continuum are provided in main text and adjusted within the ranges of the various assessment to balance the budget (Section 5.2.1.5).

Canadell, J.G., P.M.S. Monteiro, M.H. Costa, L. Cotrim da Cunha, P.M. Cox, A.V. Eliseev, S. Henson, M. Ishij, S. Jaccard, C. Koven, A. Lohila, P.K. Patra, S. Piao, J. Rogelj, S. Syampungani, S. Zaehle, and K. Zickfeld, 2021: Global Carbon and other Biogeochemical Cycles and Feedbacks. In *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 673–816, doi:10.1017/9781009157896.007.

Small by areal extent

Allen & Pavelsky 2018 Science



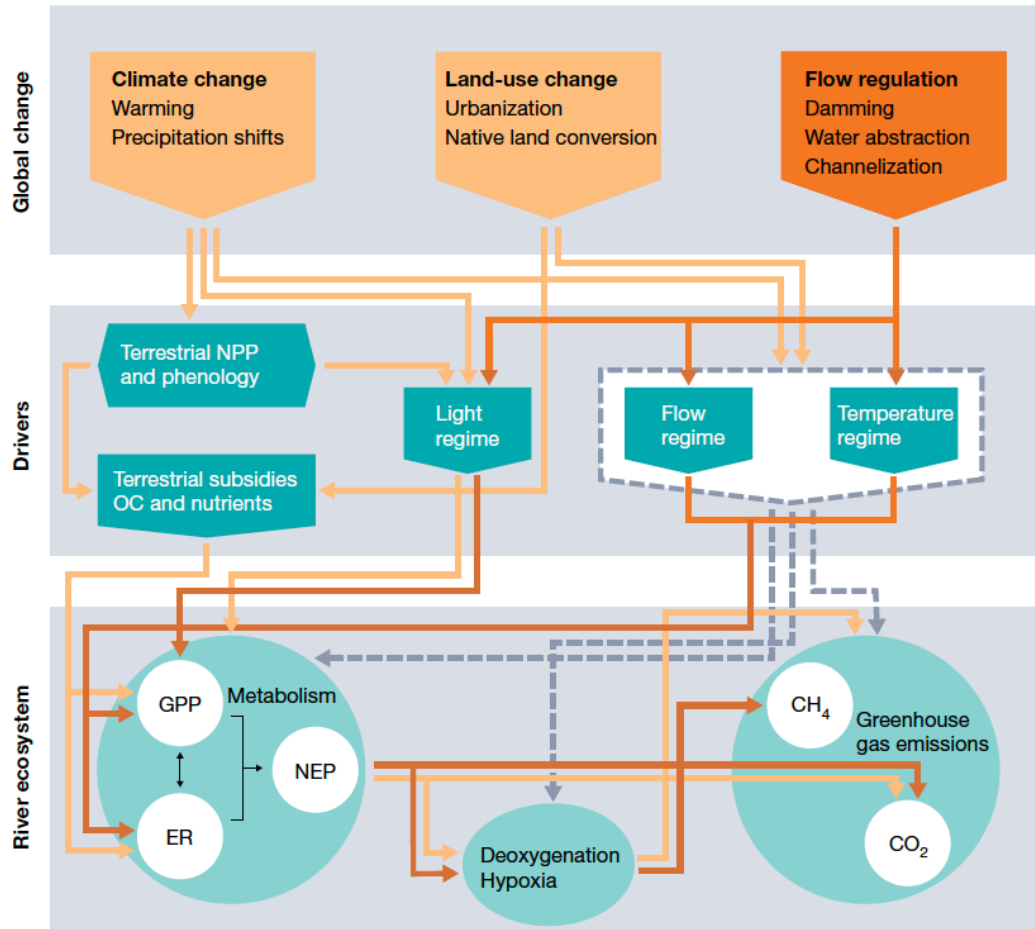
Earth: 510 million km²

Ocean: 360 million km²

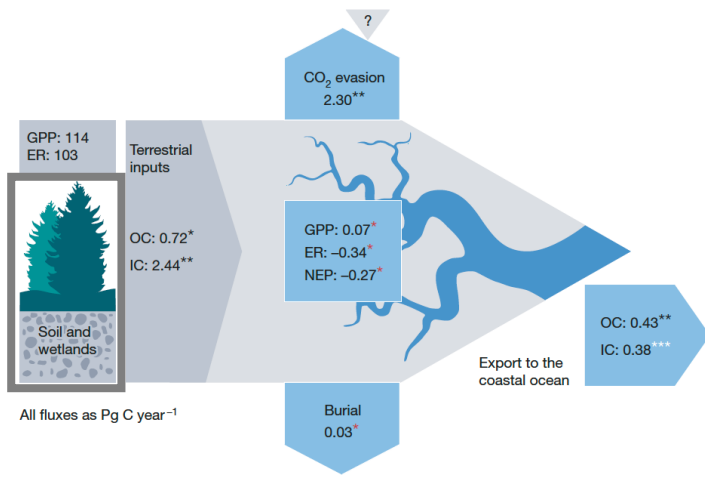
Rivers: 0.773 million km²

(0.58% of non-glaciated land surface)

Global change, river ecosystem processes and biogeochemistry

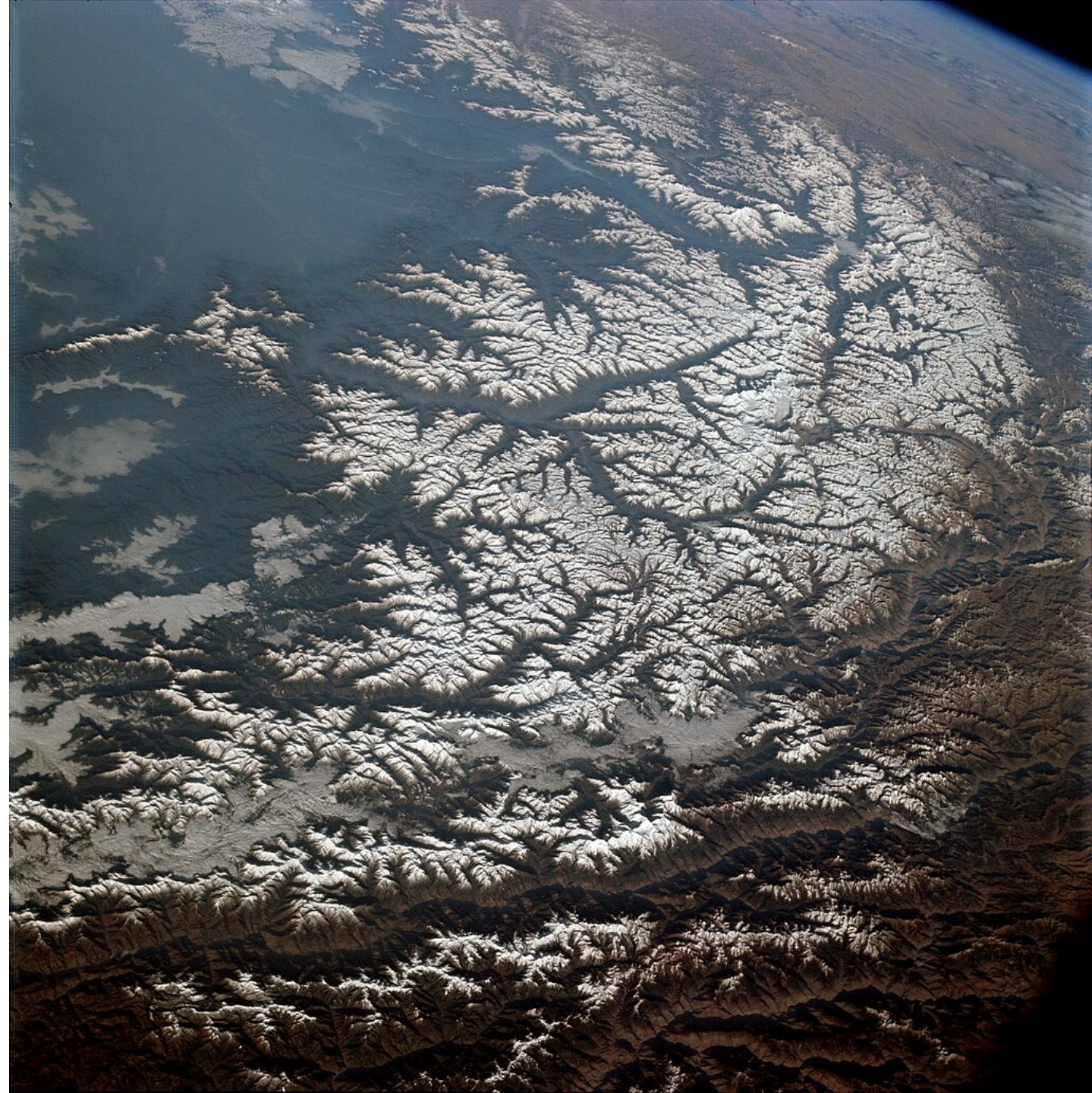


- Global-change impacts on river ecosystem processes and related biogeochemistry complex and poorly understood.
- Intricate connection with the terrestrial environment and coupling of physical, chemical and biological processes.



Mountains account for 25% of Earth's land surface and their streams contribute more than 30% to global runoff.

Mountains are highly vulnerable to climate change.

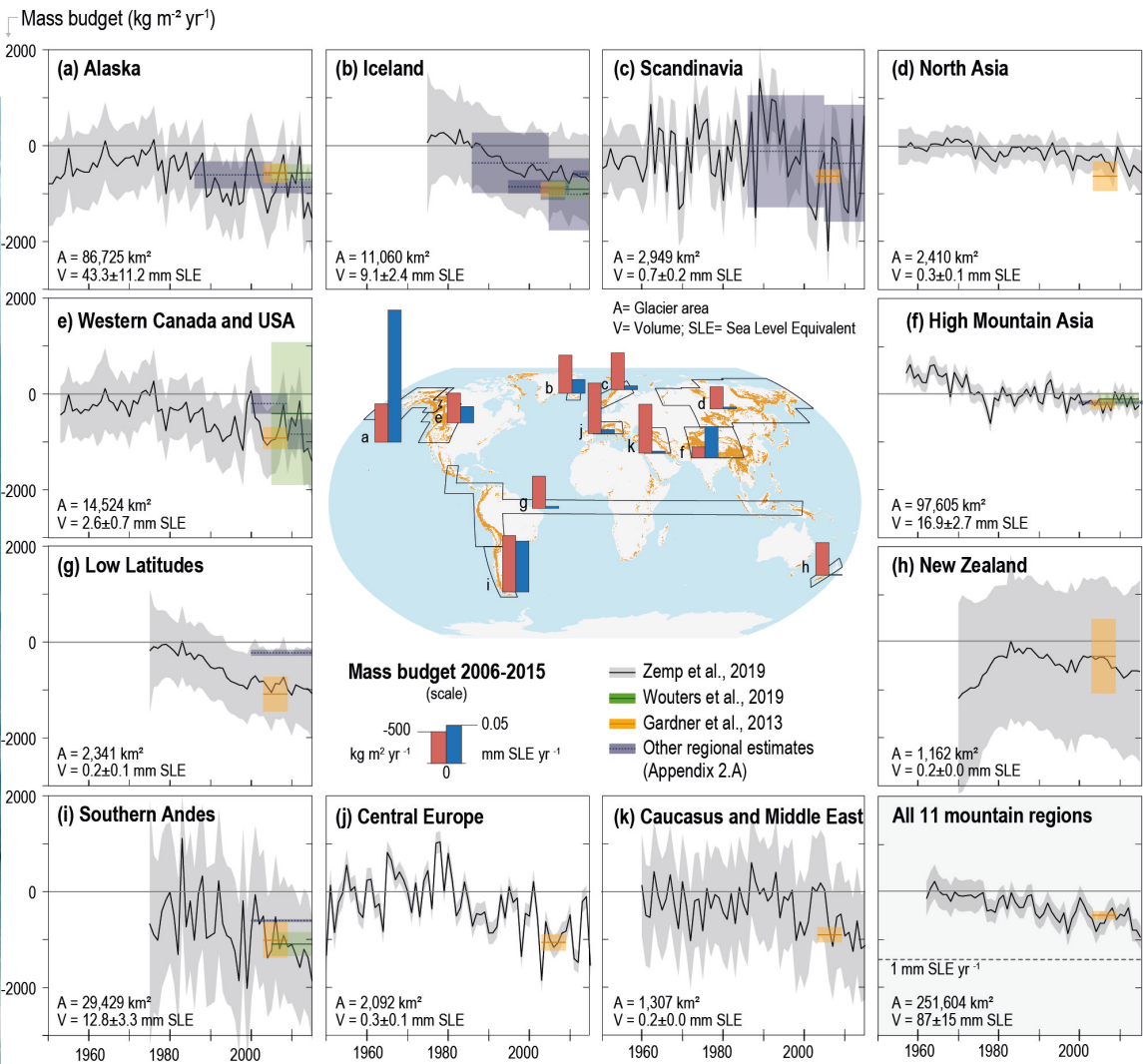


Mountains are highly vulnerable to climate change



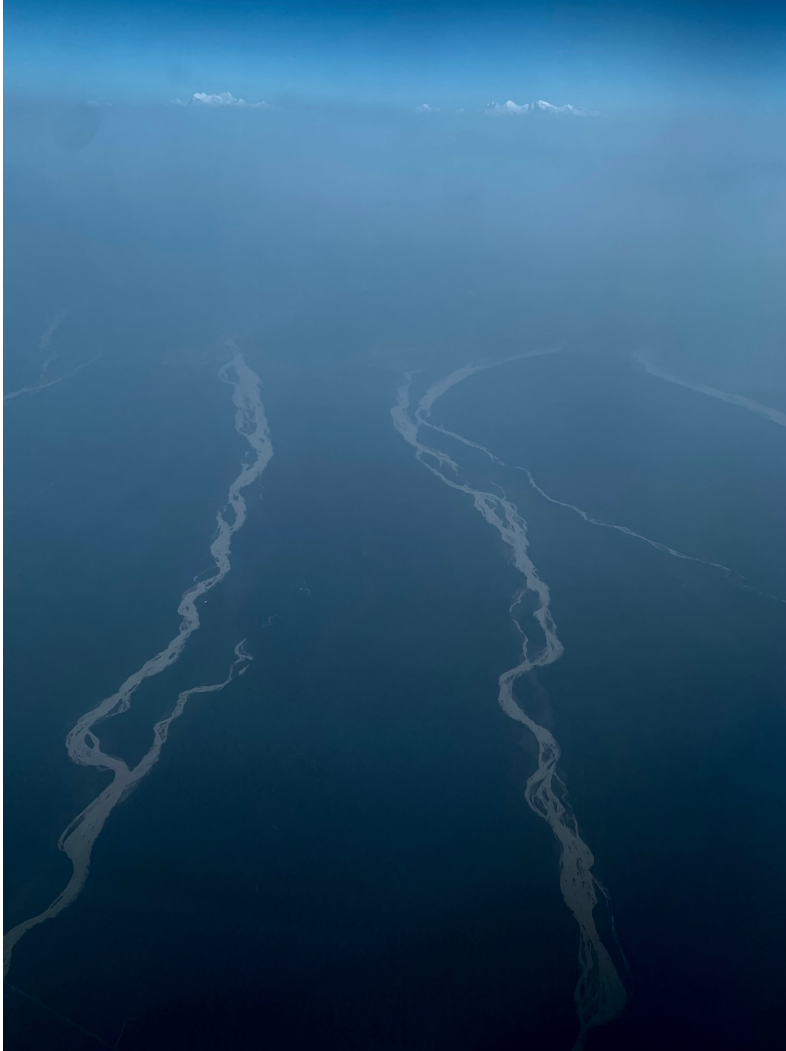
APA/EXPA/JFK

Climate warming and glacier melt

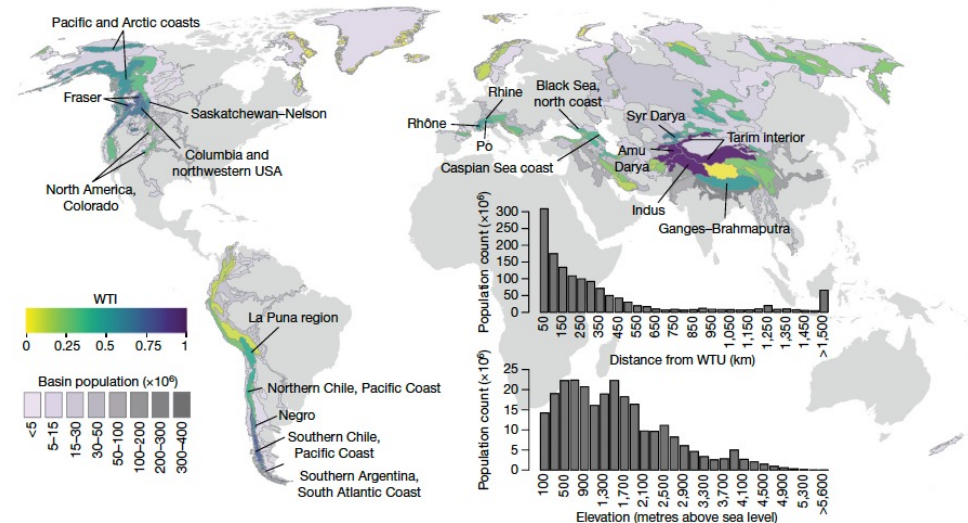


Consequences of melting mountain glaciers

Vanishing water towers



Millions of people rely on water from the world's glaciers



Immerzeel et al. 2029 Nature

An aerial photograph of a high-altitude mountain valley. A large glacier is melting in the upper center, feeding a river that flows down the valley. The river has a braided pattern with many small channels and is filled with sediment. The surrounding mountains are rugged and covered in snow and ice. The foreground shows a forested area at the bottom of the valley.

Consequences of melting glaciers

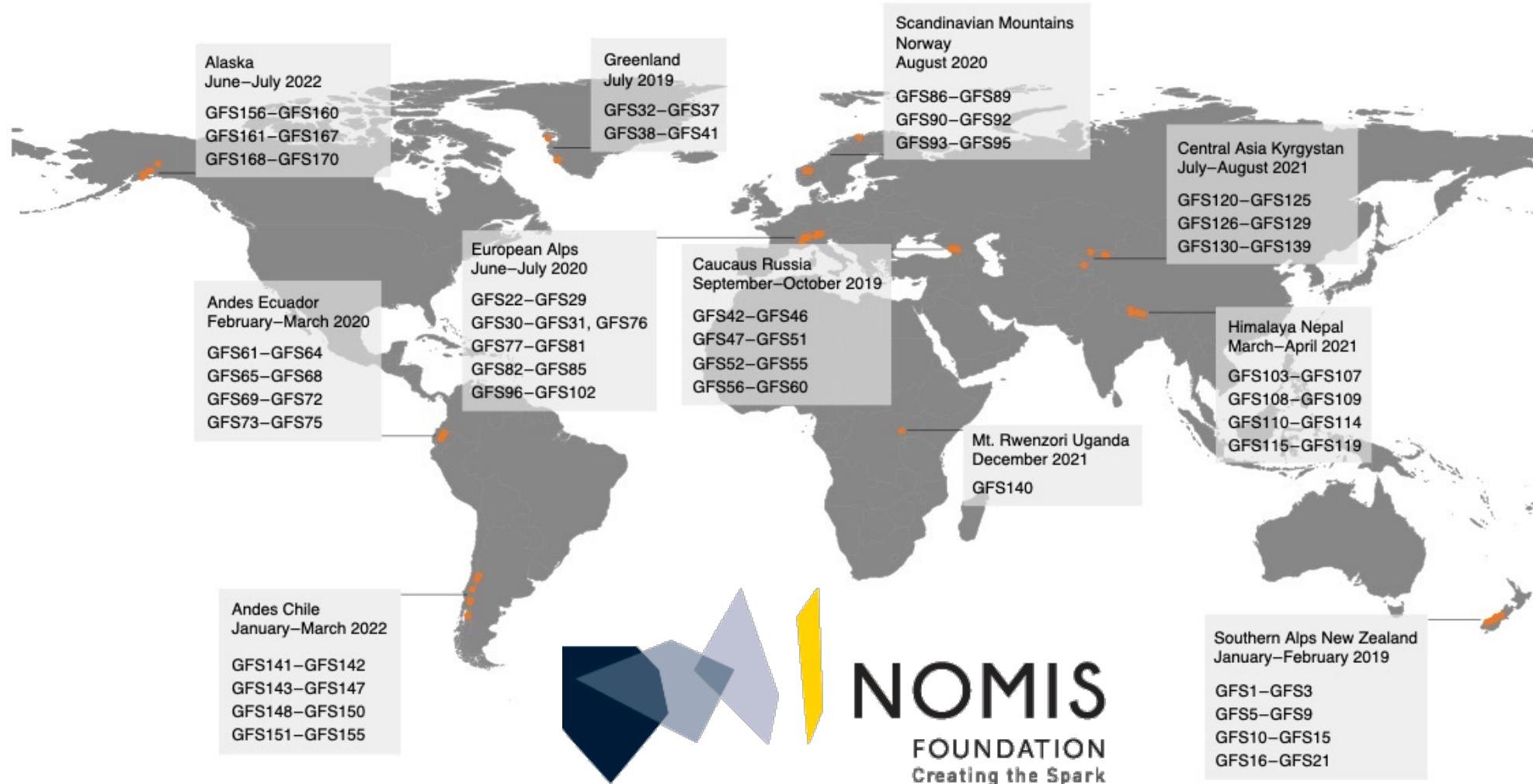
How do glacier-fed stream ecosystems react to global warming?

Cruising the roof of our planet



Cruising the roof of our planet

171 glacier-fed streams worldwide



Glacier-fed streams

Interface between the cryosphere and hydrosphere

- Freezing cold
- Long darkness in winter
- High UV-radiation
- High turbulence
- Unstable sediments
- Ultra-oligotrophic (like the deep sea)



An amazing 'field team'

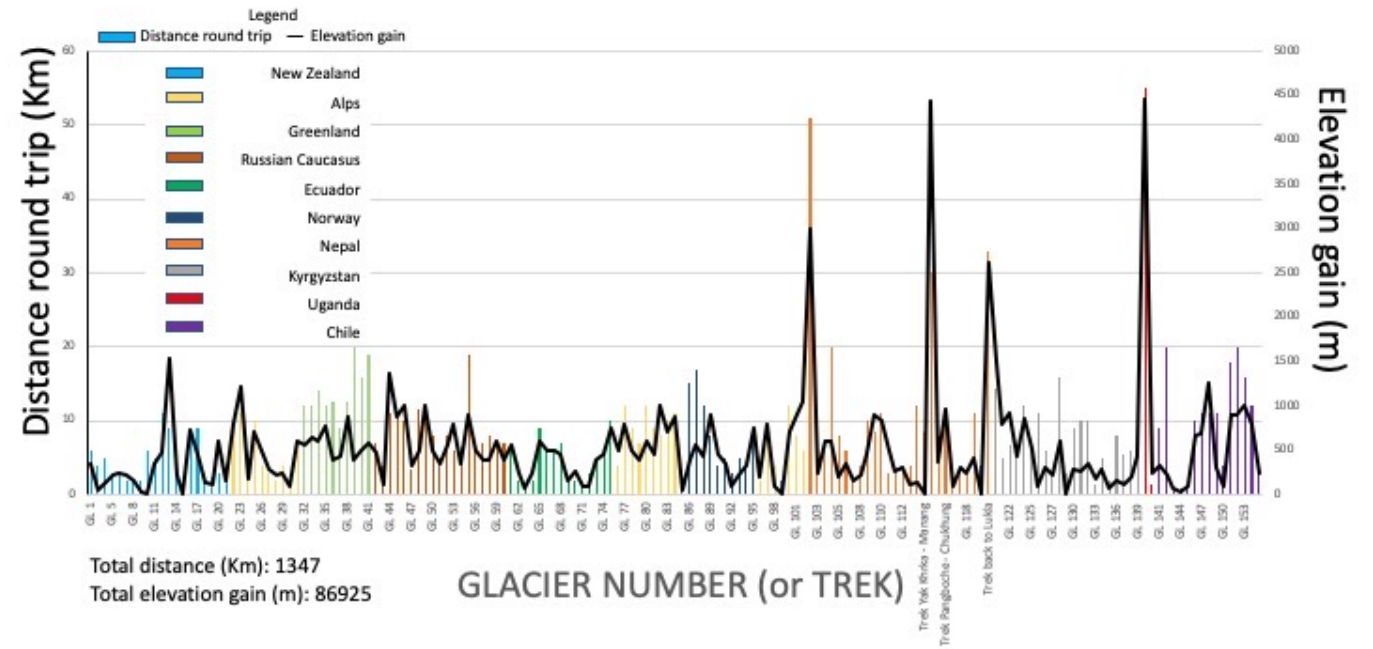
Mike Styllas, Martina Schön, Matteo Tolosano, Vincent de Staercke



Cruising the roof of our planet



1347 km
87 km



16,585 samples

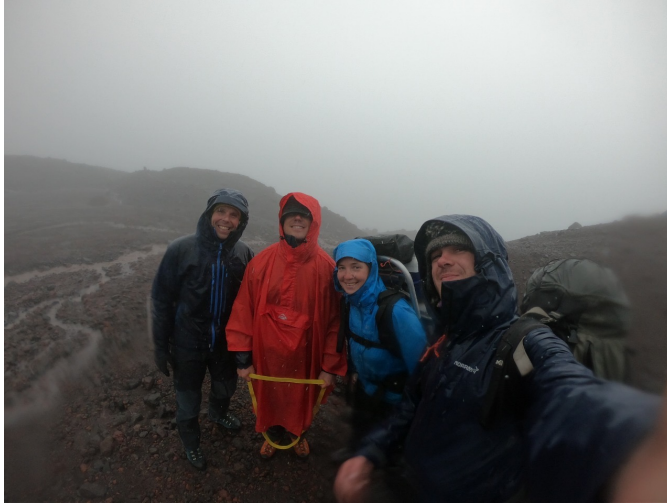
Népal LES SCIENTIFIQUES AU CHEVET DES GLACIERS

Depuis 2018, les équipes de Vanishing glaciers se rendent sur les plus hauts sommets du monde entier. En expédition dans l'Himalaya, nous avons suivi cinq scientifiques à la recherche de la forme de vie la plus ancienne sur terre : les microbes. Et il y a urgence : le réchauffement climatique accélère la fonte des glaces et c'est toute une biodiversité encore inconnue qui s'éteint.

De nos envoyées spéciales Fanny Arlandis (texte) et Sophie Rodriguez (photos)

Prélèvements de sédiments
par Martina Schön, au
pied du glacier Kinshung, à
4 400 mètres d'altitude.

A team with outstanding qualities



③ RABIPUR Tollwut/Rage	02.03 2021	DATE: 01/02/21 JUE RABIPUR lot: ARBA 522B	1a
Fièvre Typhoïde		Vivovif Berna Typhoid vaccine 3 caps Lot nr: 003487	10
COVID-19	10.02 2021	Moderna ● OSML N° lot: 300042723	
COVID-19	26.3 2021	Moderna ● OSML N° lot: 3001530	
Twinnix™ 720/20 Hépatite A+B	02.03 2021	Twinnix™ 720/20 Hep.A+B Lot: AHAB396AA	3e/s



Expedition logistics

Keeping the cryopreservation chain unbroken — from the field to Lausanne



Expedition logistics

Food, hiring porters and guides



Weight	
Donkeys	Food 30 kg Resp 7.3 kg 191
	Wido 21.0 kg Boellp 7.5
	Porters 32 kg 5 204
Box 1	15 kg 18
Box 2	20 kg 122
Box 3	6.5 kg 133.5
Box 4	9.5 kg 153
Box 5	14.0 kg 167
Box 6	17.3 kg 184.3
Box 7	21.0 kg
Duffel 1	18.0 Mattres
2	10.0 Vineer 48
3	10.5 Sophie 136.5
4	13.0 Penny 66
5	20.1 kg Tom 86
6	16.0 kg Mike 102
7	14.5 kg 1160
4 porters	
Generator	38 kg
Cases	25 kg 1 Petrol
Tent	8.0 kg 211 3 kg
T 45	18 kg 92
Unit	10 kg 102
Toilet tent	3.7 kg 1037
Vegetables	4.2 kg 102
Food	18.0 kg 126
Food	18.5 kg 144
Porter food	15.4 kg 159
Dive	25.0 kg 183
Fruit	12.0 kg 19201

Food	8.7 kg 192 201
Dive	30 kg 231
Vegetables	27.0 kg 257
Dhal	23.0 kg
Tomatoes	30 kg
Eggs	12.8 kg 286
Stove	2.3 kg 288
Box TP	16.3 kg 300
Mattress	3.5 x 2 = 7.0 kg 31
Mattress	15.0 kg 1326
Box Food Rope	22.0 kg 313
Chicken	14.0 kg 362
Dhal	8.0 kg
300	
208	
598	
116	
714 kg	



Thanks to the more than 150 porters, guides and helpers in
Nepal, Uganda, Kyrgyzstan, New Zealand, Norway, Greenland,
Chile, Ecuador, Russian Caucasus, and Alaska



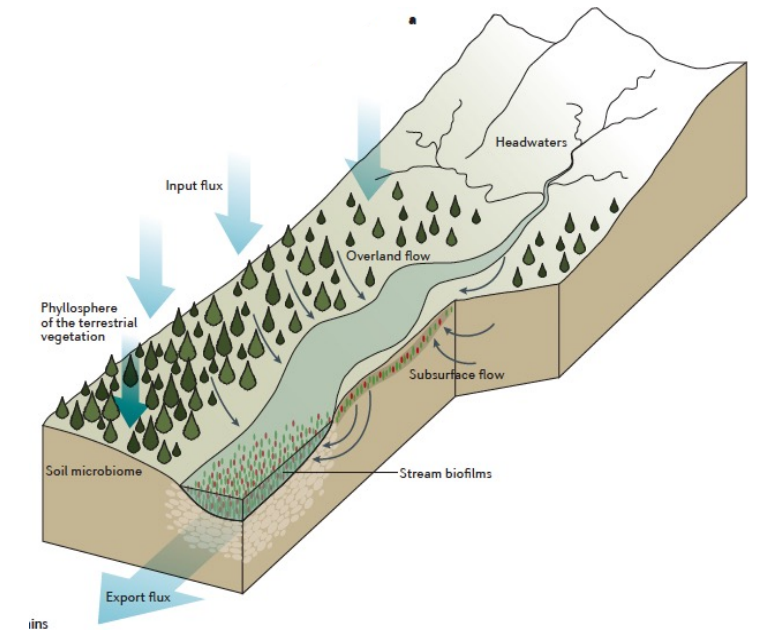
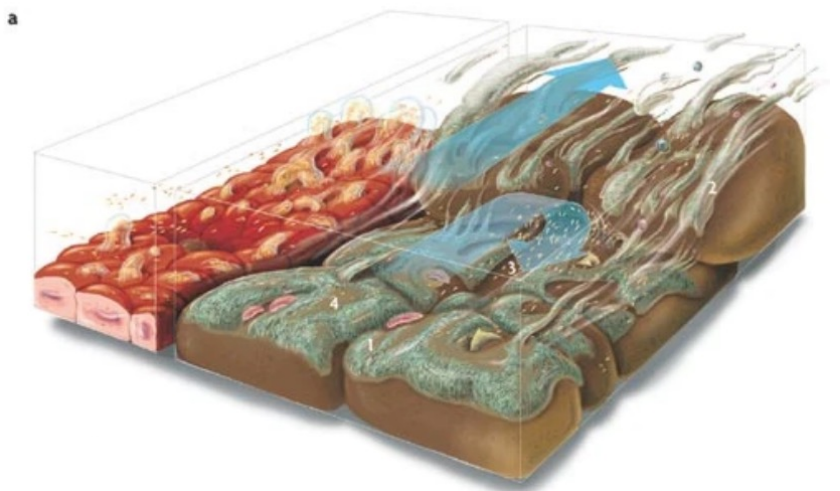
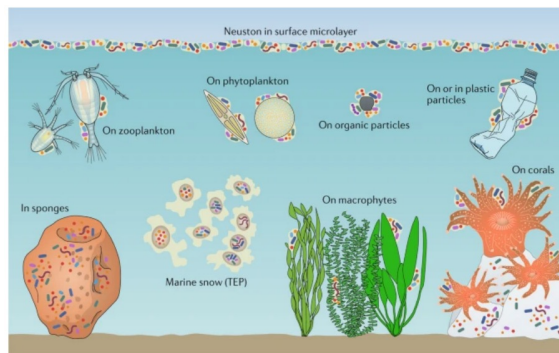
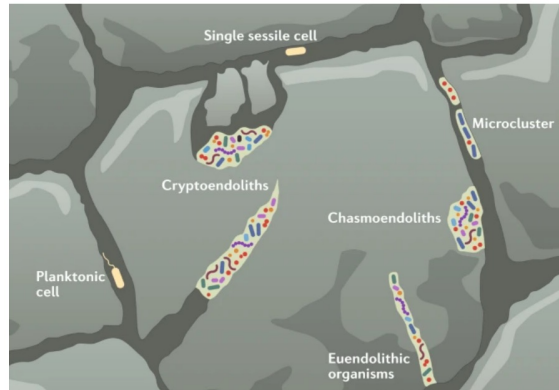
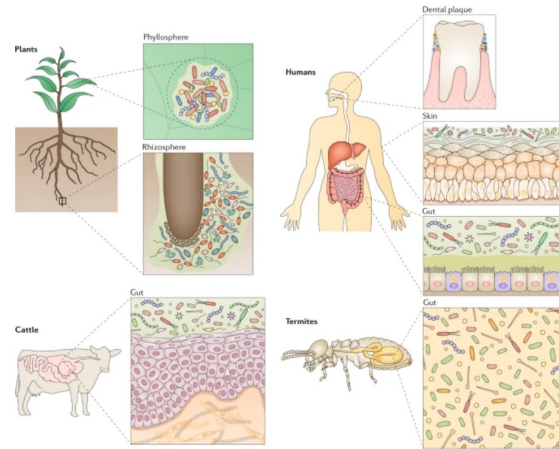
Microbial biofilms

Dominate life in glacier-fed streams



Microbial biofilms

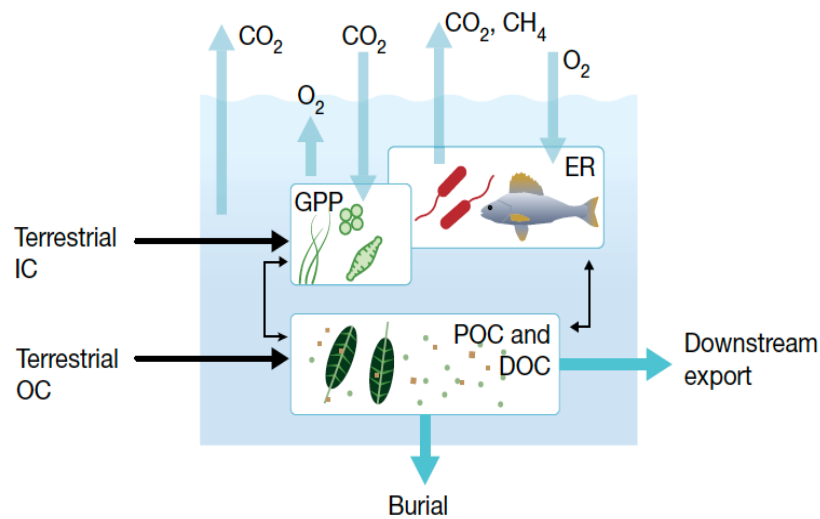
Most successful form of life over 3.2 billion years



Flemming and Würtz 2019 Nature Review Microbiology
 Battin et al. 2016 Nature Review Microbiology
 Battin et al. 2007 Nature Review Microbiology

Why microbial biofilms?

Microorganisms are the 'conductors' of Earth's biogeochemical cycles



Understanding the link between microbes, ecosystem processes and biogeochemistry

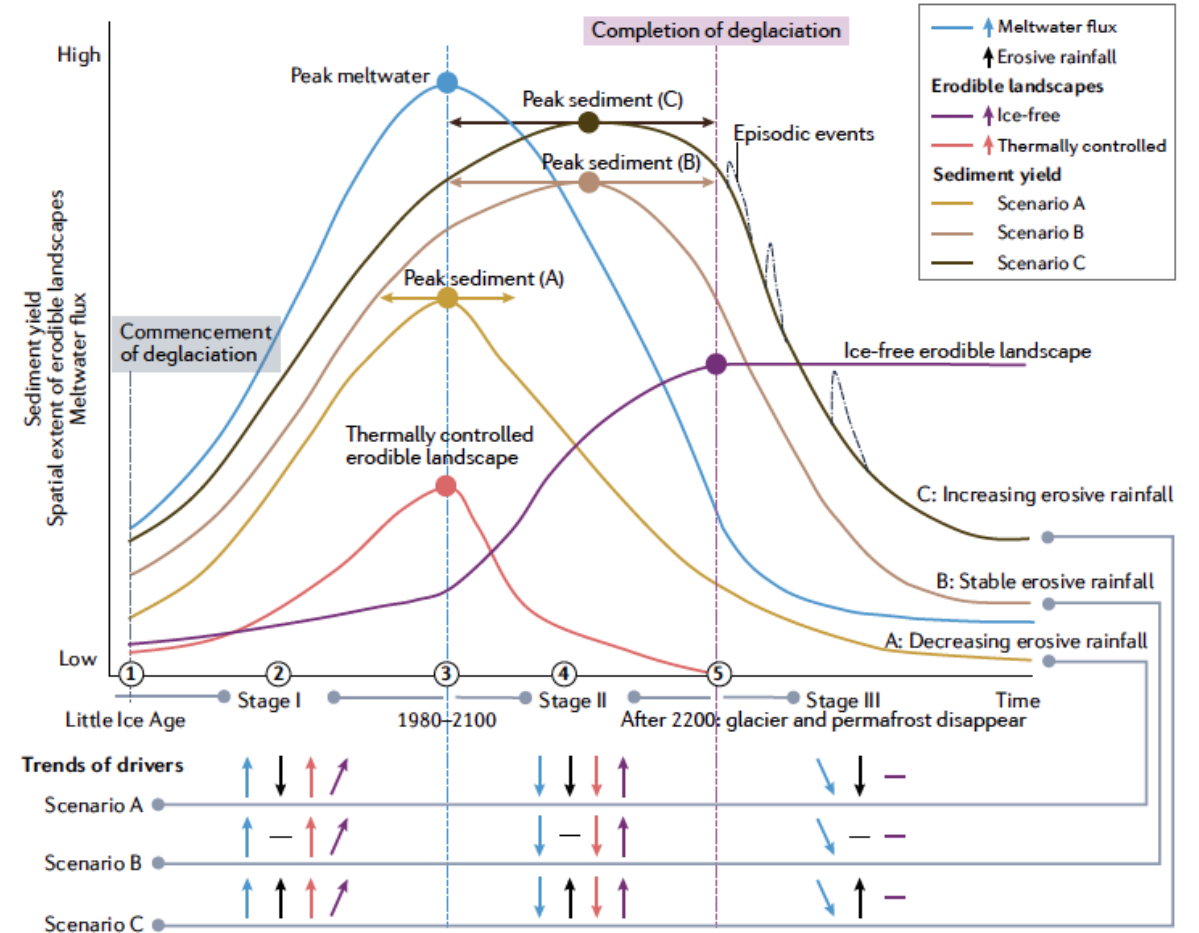


The scientific approach

- Meltwater runoff and downstream water flow decrease
- Less sediments produced and transported downstream
- Streamwater temperature increases

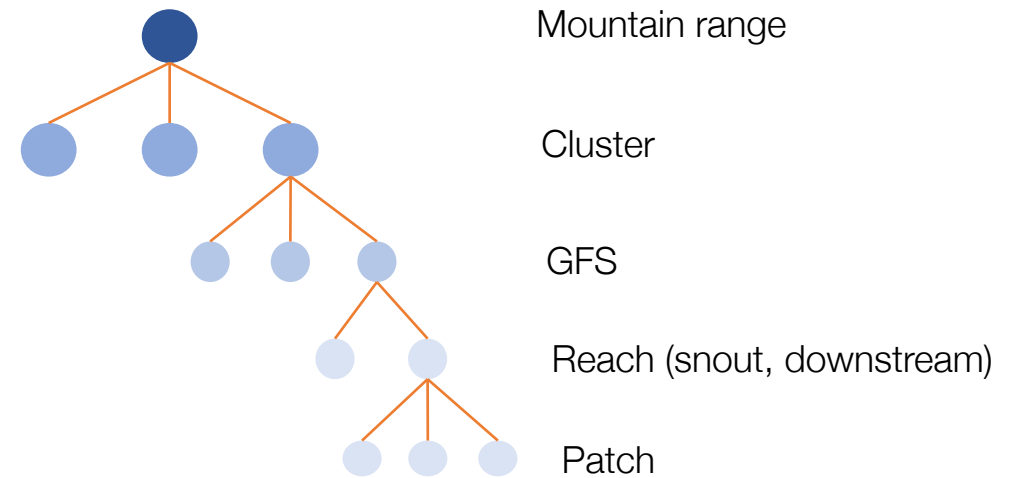
Glacier size, water flow, temperature and suspended sediments are master variables of the glacier-fed stream environment

Space-for-time substitutions

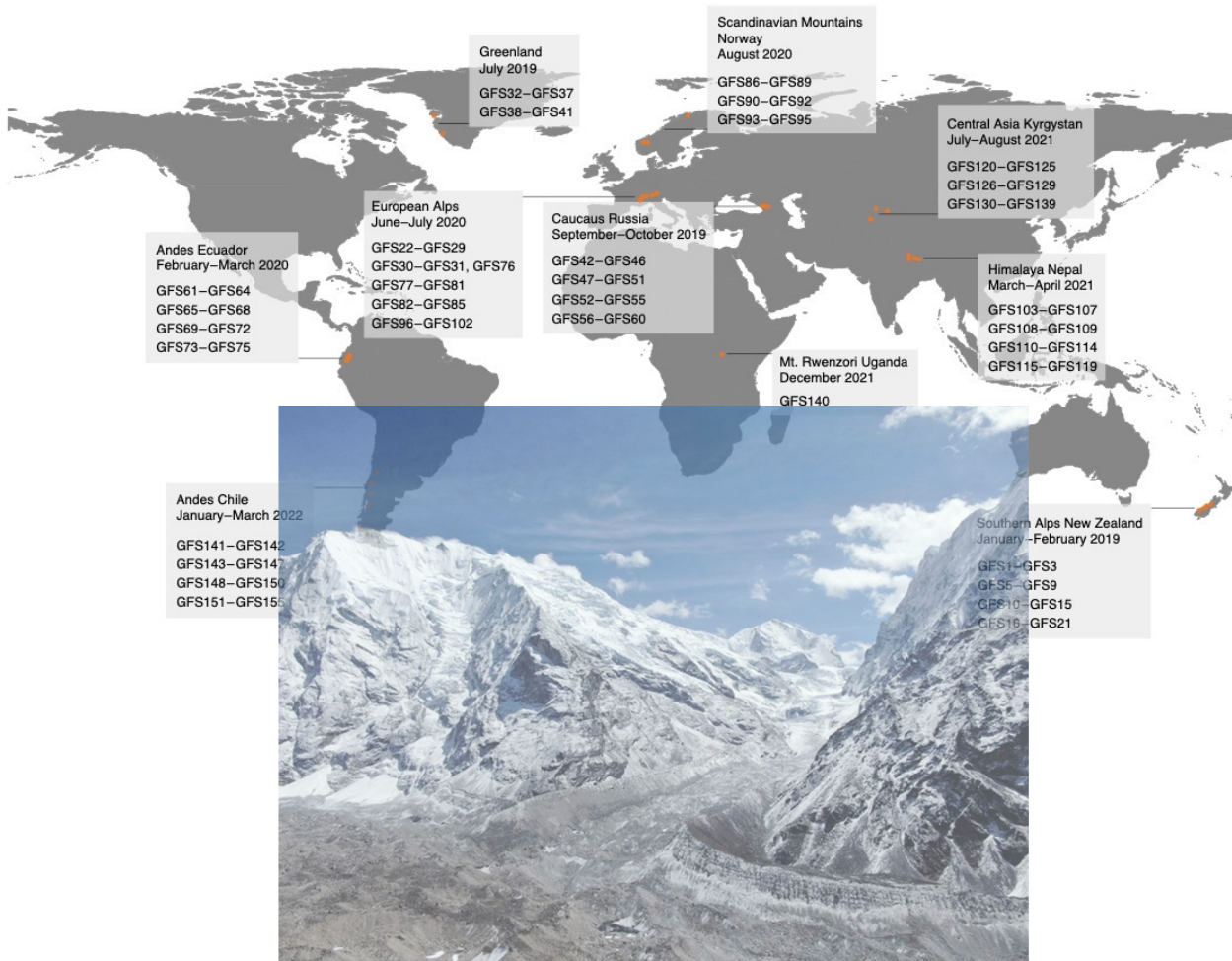


Zhang et al. 2023 Nature Reviews Earth and Environment

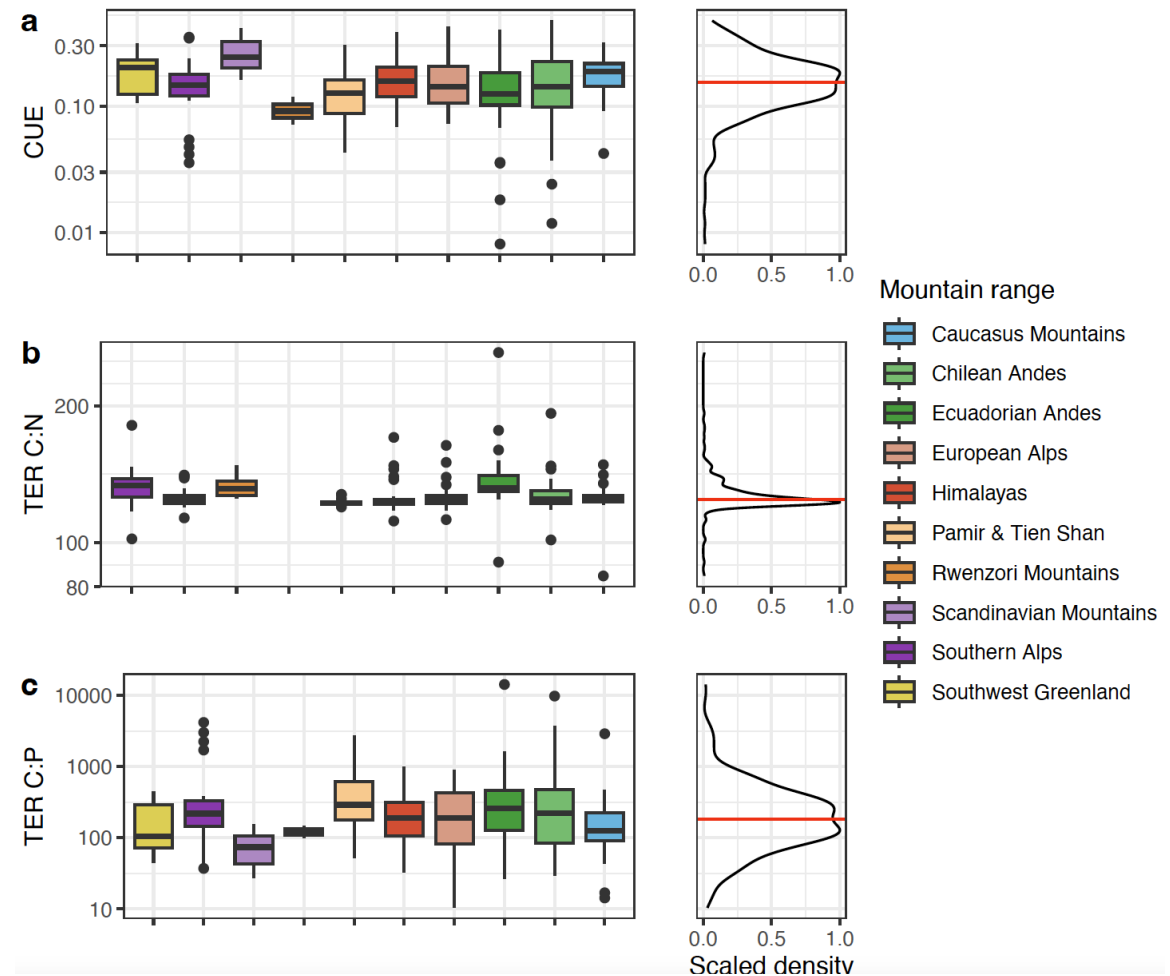
Nested sampling design



- Microbial biomass
- 16S & 18S rRNA, metagenomics
- Extracellular enzymes, bacterial carbon production, etc...
- Glaciology, geology, mineral composition
- GFS water physico-chemistry



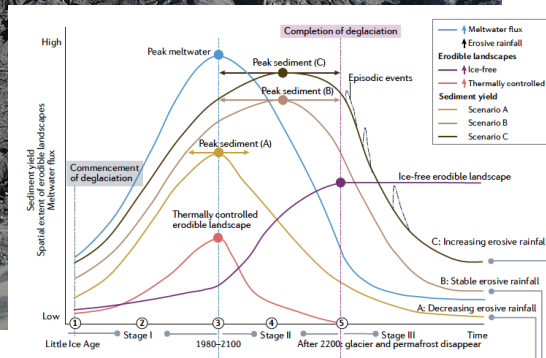
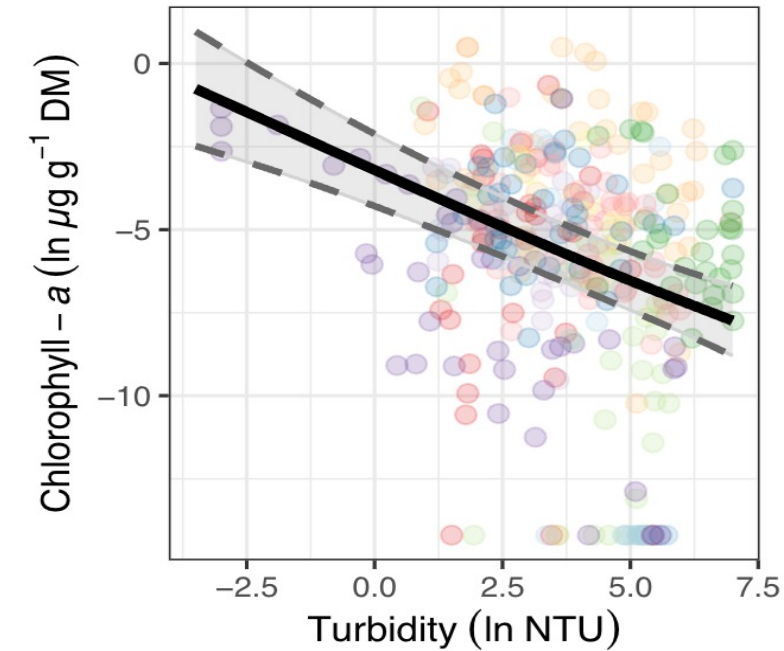
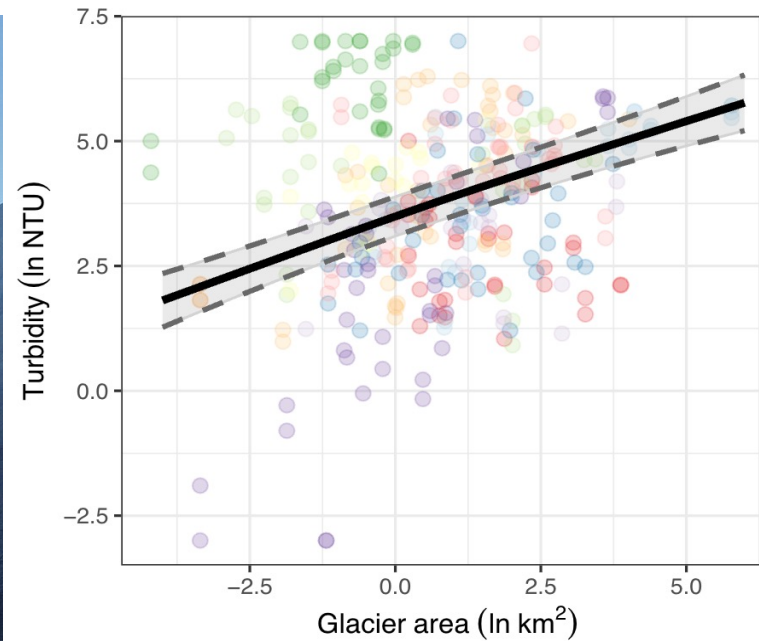
Resource limitation and microbial starvation



- Microbial metabolism limited by carbon and phosphorus
- Low microbial carbon use efficiency (median: 0.15)
- Starvation and little growth

A 'green transition' takes place

A space-for-time substitution approach

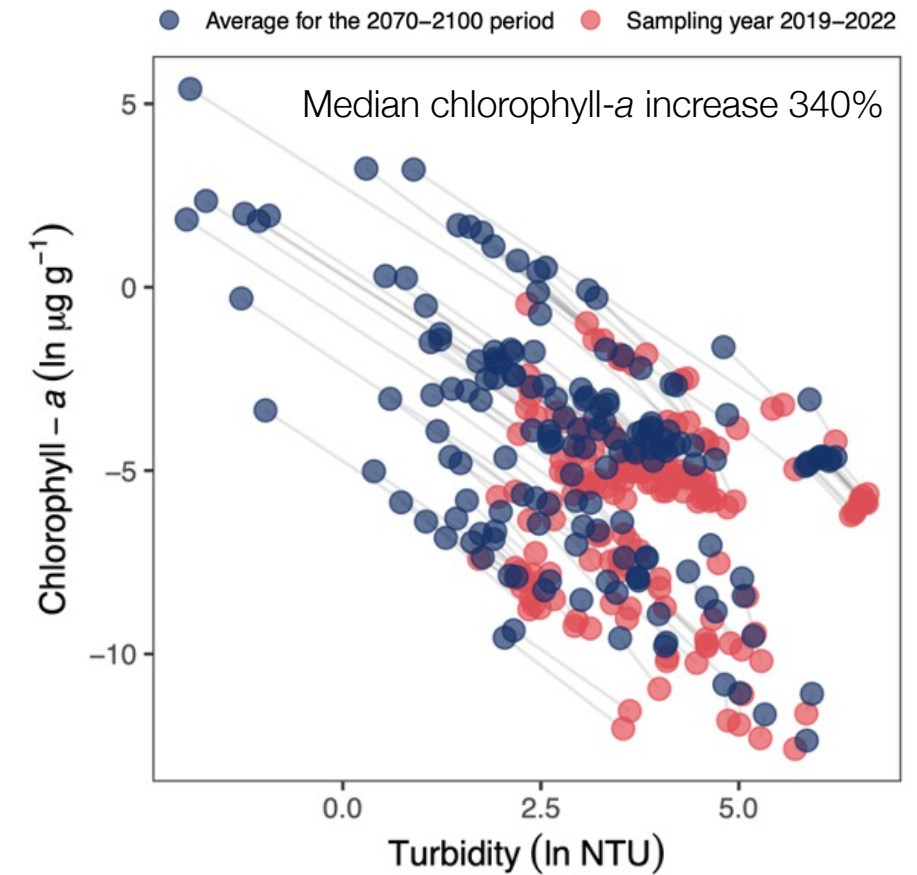
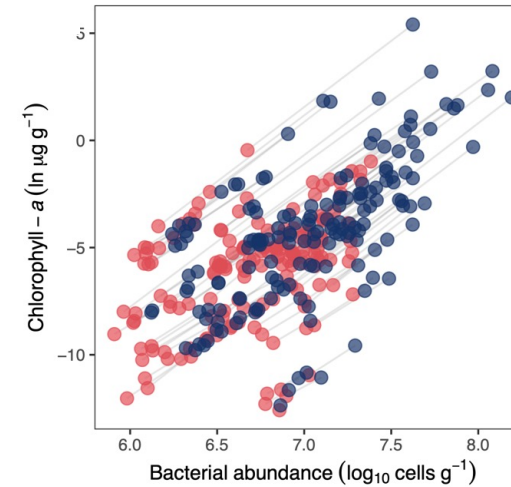
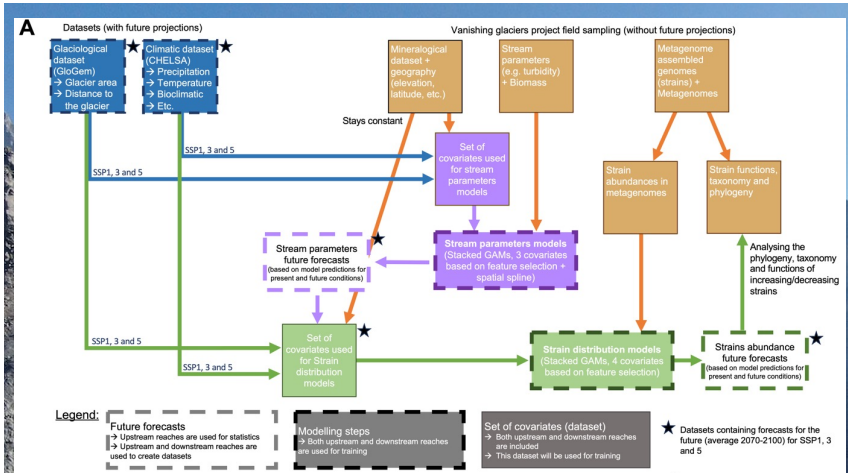


Global trends indicate

- Streamwater turbidity decreases as glacier
- More light reaches the stream bottom
- Algal biomass is stimulated and streams become greener

A 'green transition' takes place

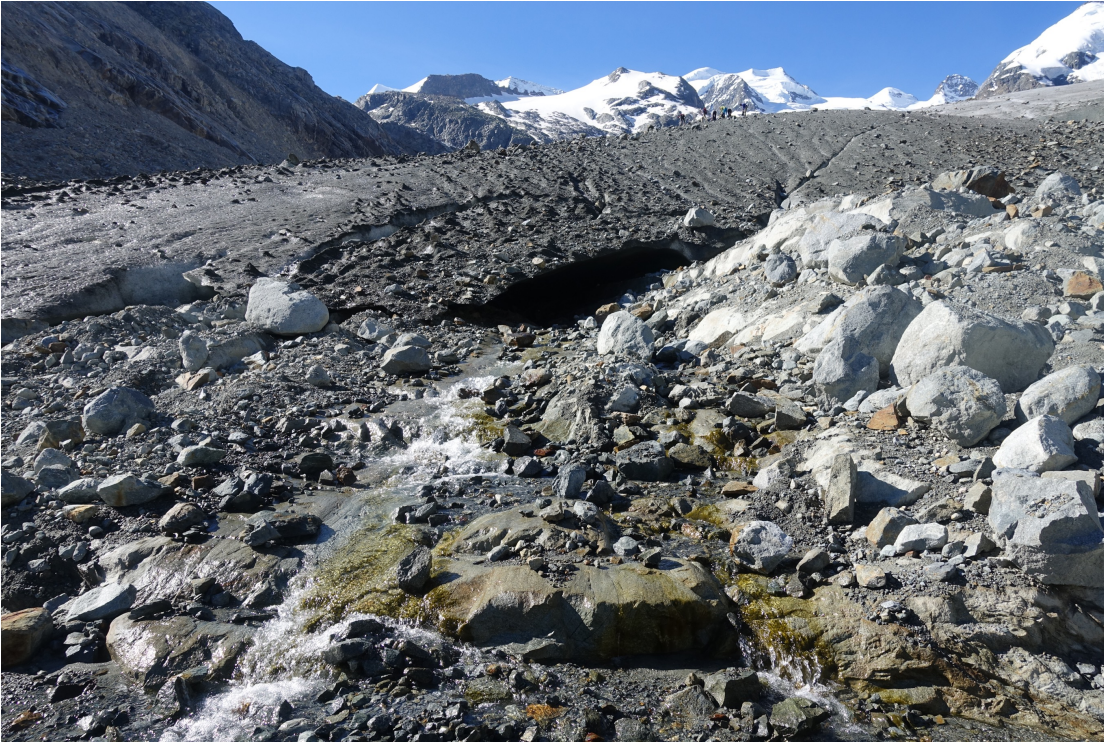
Modelling climate-change scenarios



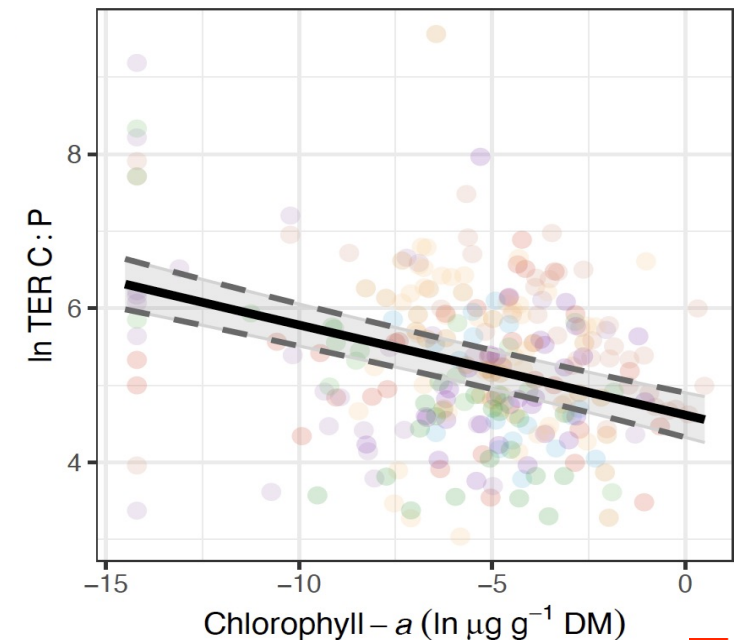
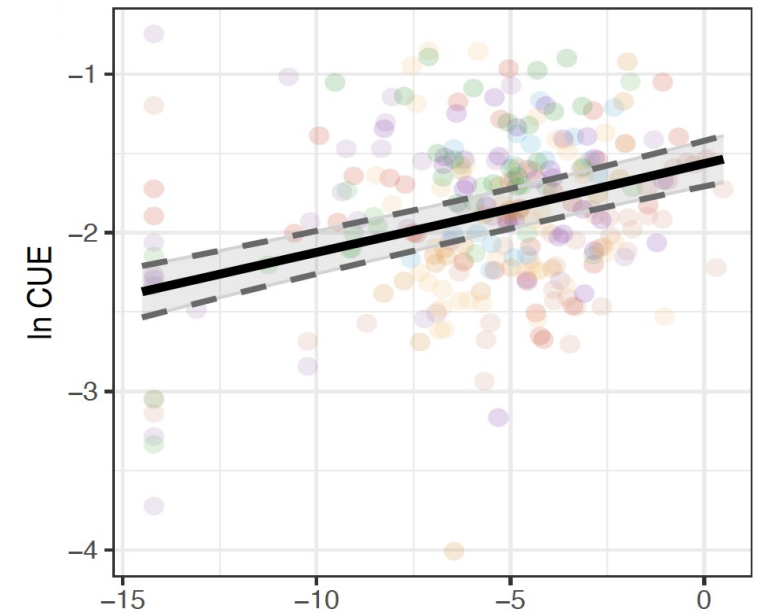
Global trends indicate

- Streamwater turbidity decreases as glaciers shrink
- More light reaches the stream bottom
- Algal biomass is stimulated and streams become greener
- Greening promotes bacterial growth

A 'green transition' takes place

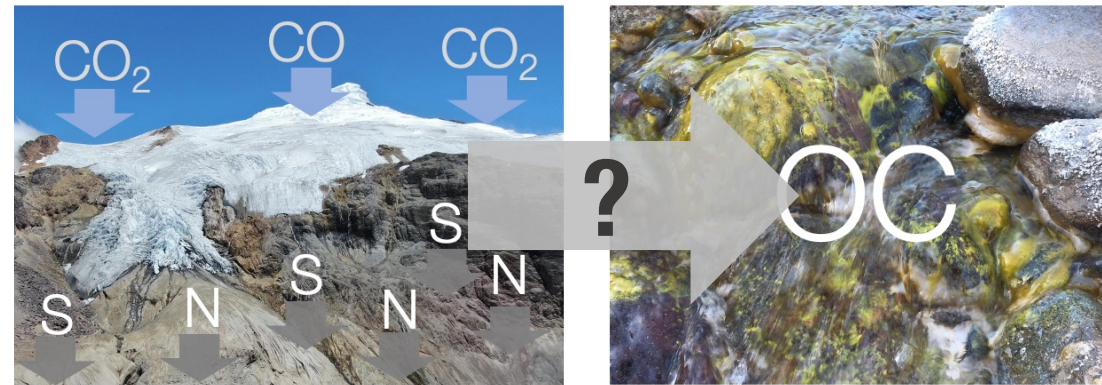
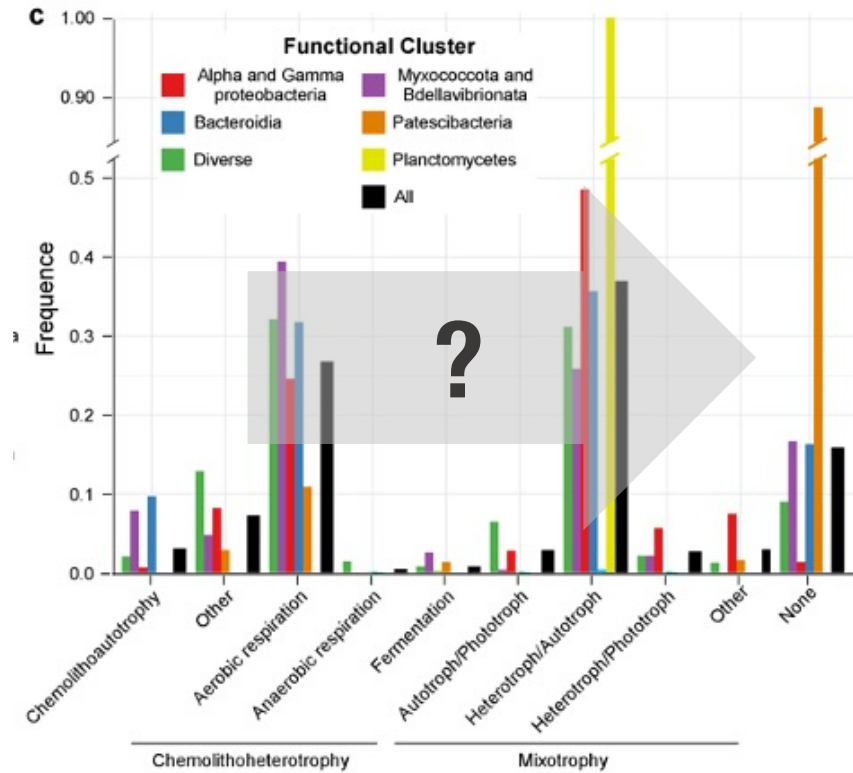


- Algae provide organic carbon as a resource to the microbial metabolism
- Relieves microbes from energy limitation and starvation
- Increases carbon use efficiencies — relatively more organic carbon allocated to biomass growth

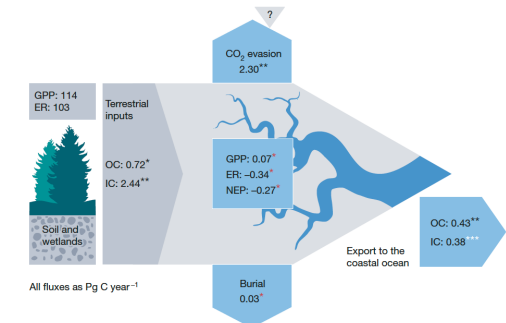


A 'green transition' takes place

Genomic evidence for shifting energetics



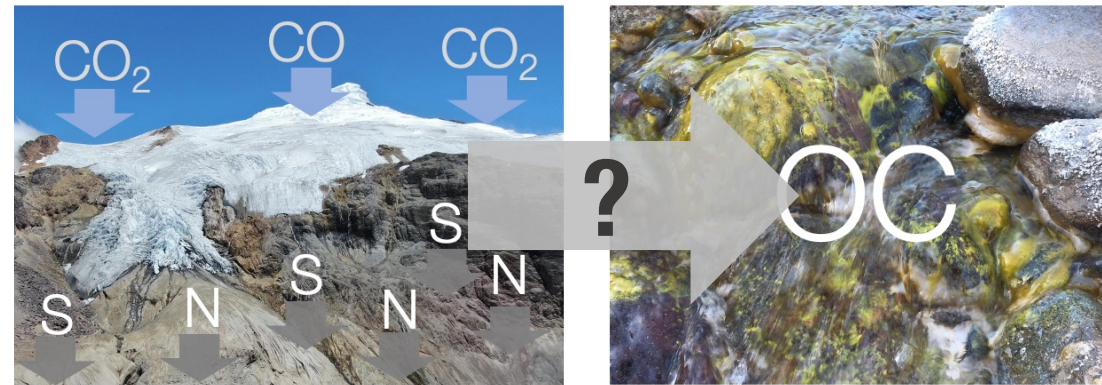
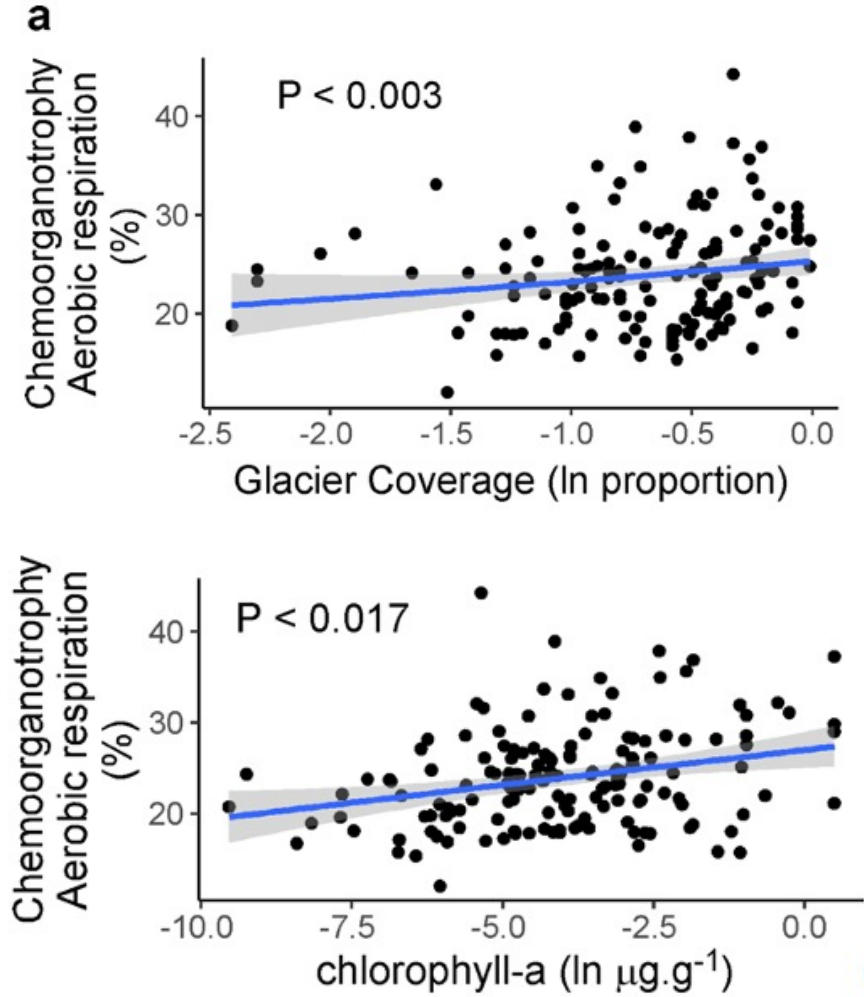
Will microbial energetics transit from chemolithotrophy to photoautotrophy, and further to heterotrophy?



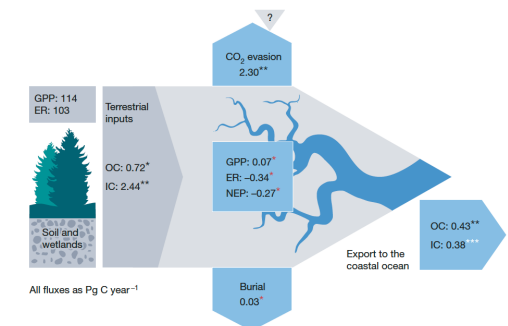
Kohler et al. 2024 Nature Geoscience
Michoud et al. 2024 Nature Microbiology

A 'green transition' takes place

Genomic evidence for shifting energetics



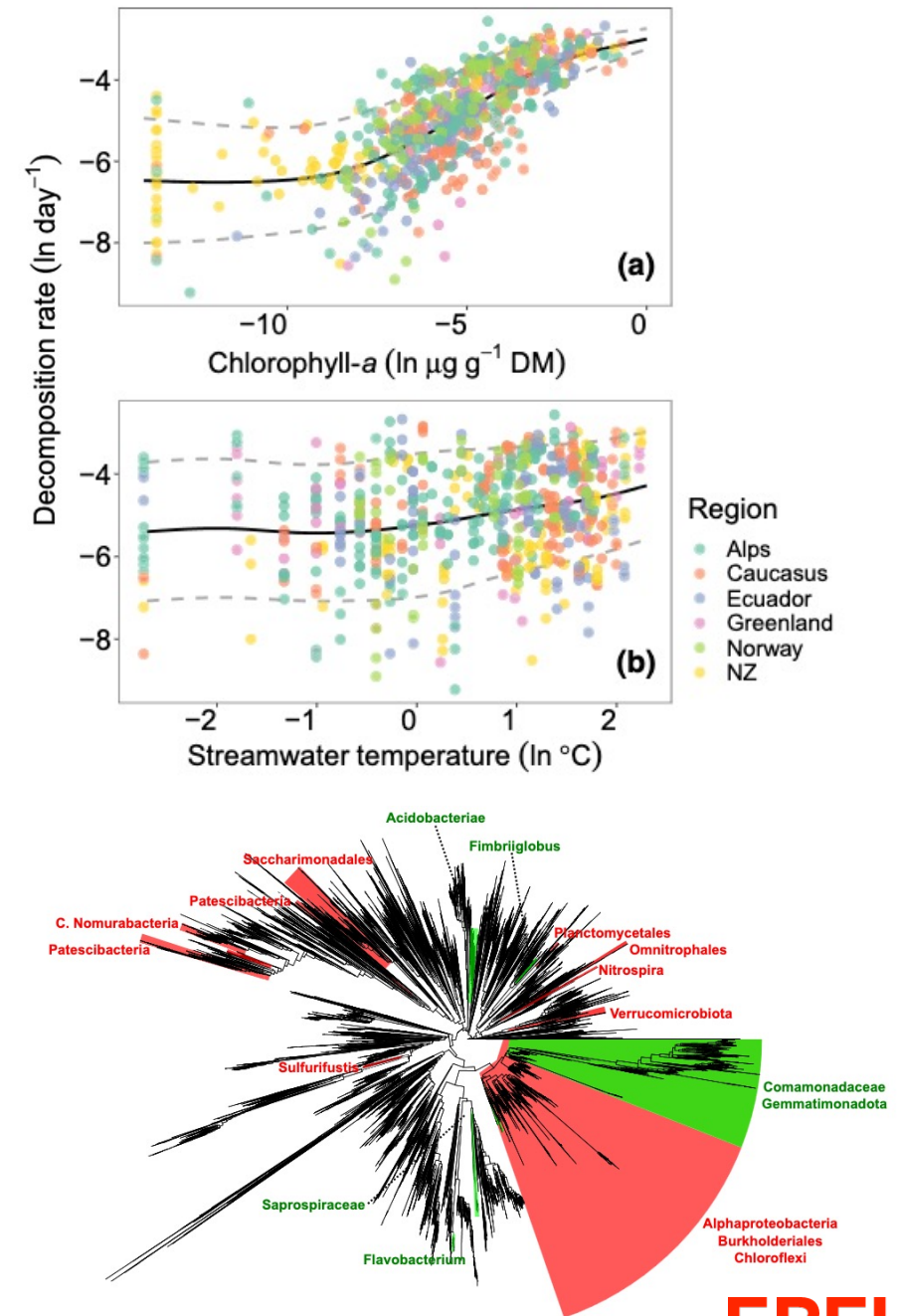
Will microbial energetics transit from chemolithotrophy to photoautotrophy, and further to heterotrophy?



The 'green transition'

Functional consequences

- Glacier shrinkage stimulates the organic matter decomposition rate
- Modulated by chlorophyll *a* and temperature
- Decomposition rate partially drives the pace of carbon cycling
- Entails a shift of the glacier-fed stream microbiome

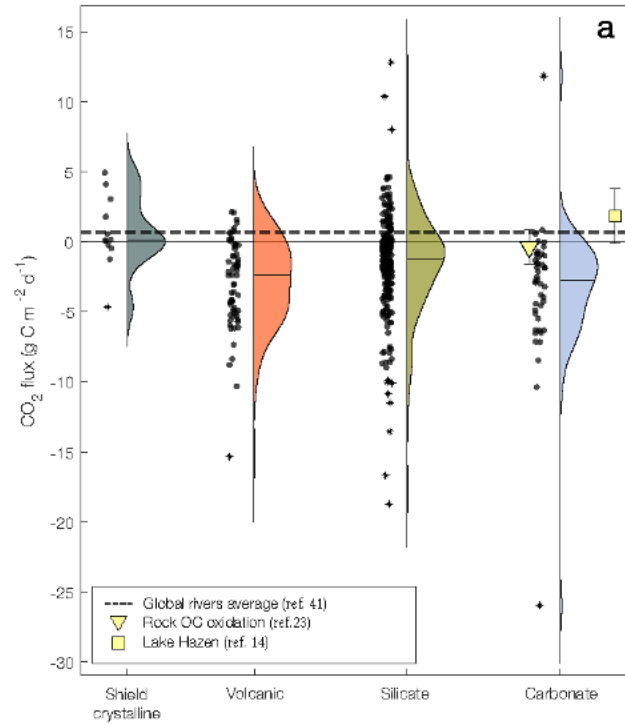




The green transition

Streams and rivers
Terrestrial ecosystems

The 'green transition' is only part of the story



- Glacierized catchments are mineral landscapes
- Chemical weathering (e.g., via carbonic acid, sulfuric acid) of minerals
- Drawdown and consumption of atmospheric CO₂
- Glacier-fed streams as sources of CO₂
- Likely in equilibrium with the atmosphere before the industrialisation



Glacier-fed streams are transitional ecosystems

- At the interface to the cryosphere, glacier-fed streams are highly vulnerable to climate change
- As glaciers melt, the environment of glacier-fed streams changes dramatically
- Impacts on the microbiome (see lecture by Hannes Peter) – losing biodiversity
- Changing microbial energetics and ecosystem functioning



From the 'world' to Valais



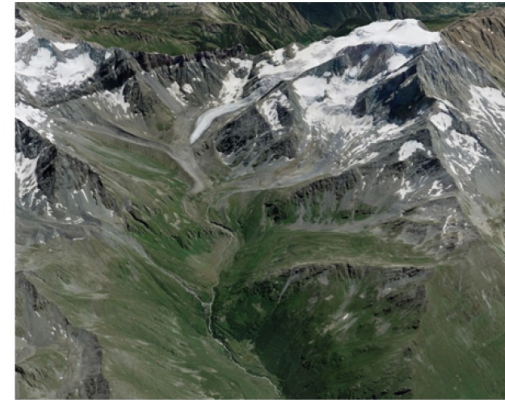
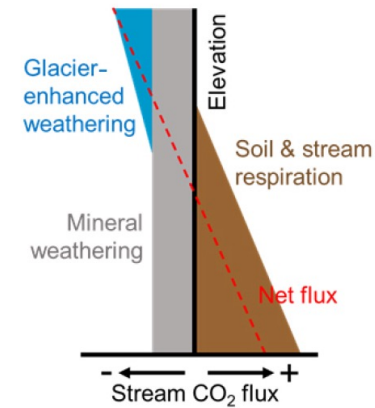
EPFL ALPOLE

Taking the 'heartbeat' of glacier-fed streams

<https://metalp.epfl.ch/>



A unique sensor network for monitoring impacts of glacier shrinkage on stream biogeochemistry

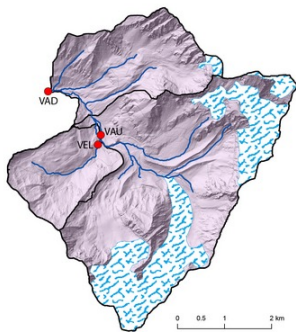


Taking the ‘heartbeat’ of glacier-fed streams

https://metalp.epfl.ch/

Our Study Sites

Explore our stations and their catchments

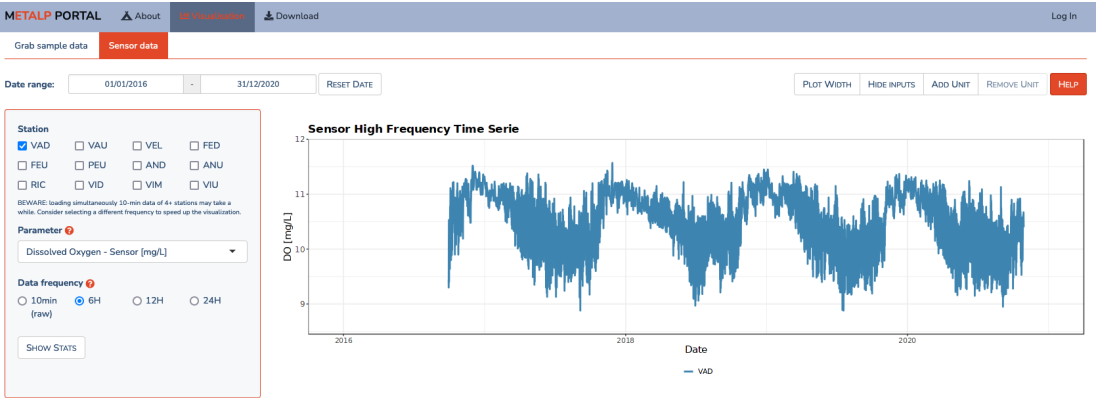
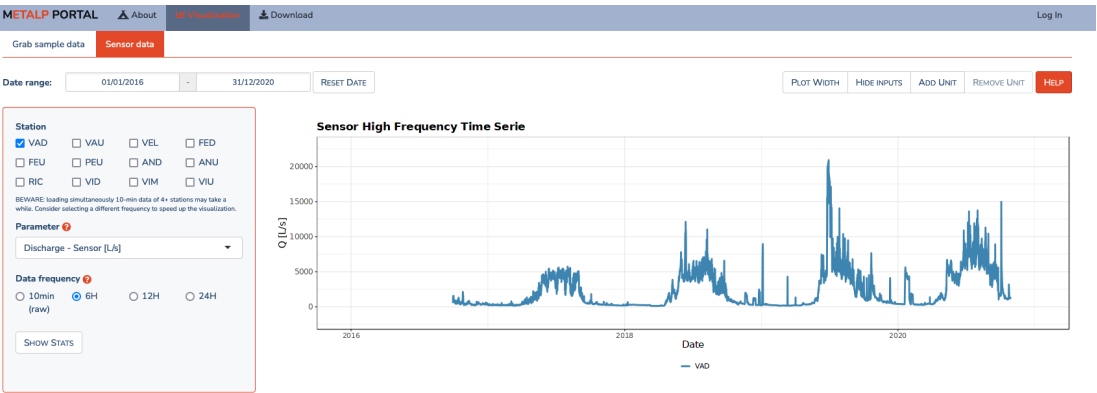
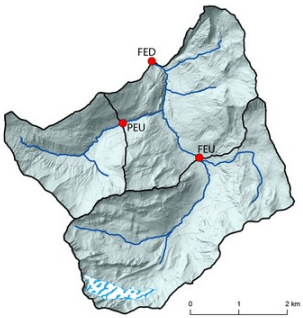


Valsorey catchment

	TORRENT DU VALSOREY DOWNSTREAM	TORRENT DU VALSOREY UPSTREAM	TORRENT DU VÉLAN
Station ID	VAD	VAU	VEL
Latitude [°]	45.935034	45.929509	45.55677
Longitude [°]	7.226898	7.244578	7.14752
Station altitude [m]	1936	2148	2161
Catchment avg alt. [m]	2868	2893	2548
Area [km2]	23.16	18.10	3.11
Vegetated area [%]	27.72	24.69	65.35
Glacier coverage [%]	22.18	27.69	0

Ferret catchment

	DRANSE DE FERRET DOWNSTREAM	DRANSE DE FERRET UPSTREAM	LA PEULE
Station ID	FED	FEU	PEU
Latitude [°]	45.905091	45.883084	45.893655
Longitude [°]	7.115597	7.130949	7.107973
Station altitude [m]	1773	1996	2024
Catchment avg alt. [m]	2421	2528	2384
Area [km ²]	20.24	9.33	3.97
Vegetated area [%]	50.07	39.60	61.19
Glacier coverage [%]	1.78	3.86	0



- Streams and rivers matter for global biogeochemical cycles despite their small contributions by areal extent
- High-mountain streams are highly vulnerable to climate change — yet poorly studied
- Glacier-fed streams are emblematic of climate change
- Transitional ecosystems — undergoing major environmental and biogeochemical shifts



Thank you for your attention!

<https://www.glacierstreams.ch/>
<https://www.epfl.ch/labs/river/>

