

An aerial photograph of a mountain valley. A river flows through the center of the valley, winding between steep, rocky slopes. The terrain is rugged and appears to be composed of dark, possibly volcanic, rock. There are some patches of snow or light-colored rock scattered throughout the landscape.

# River Ecosystems

## Microbial Life and Biogeochemistry in Alpine Rivers

Hannes Peter  
EPFL River Ecosystems Laboratory

# River Ecosystems Laboratory



# 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)**



# Rivers

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

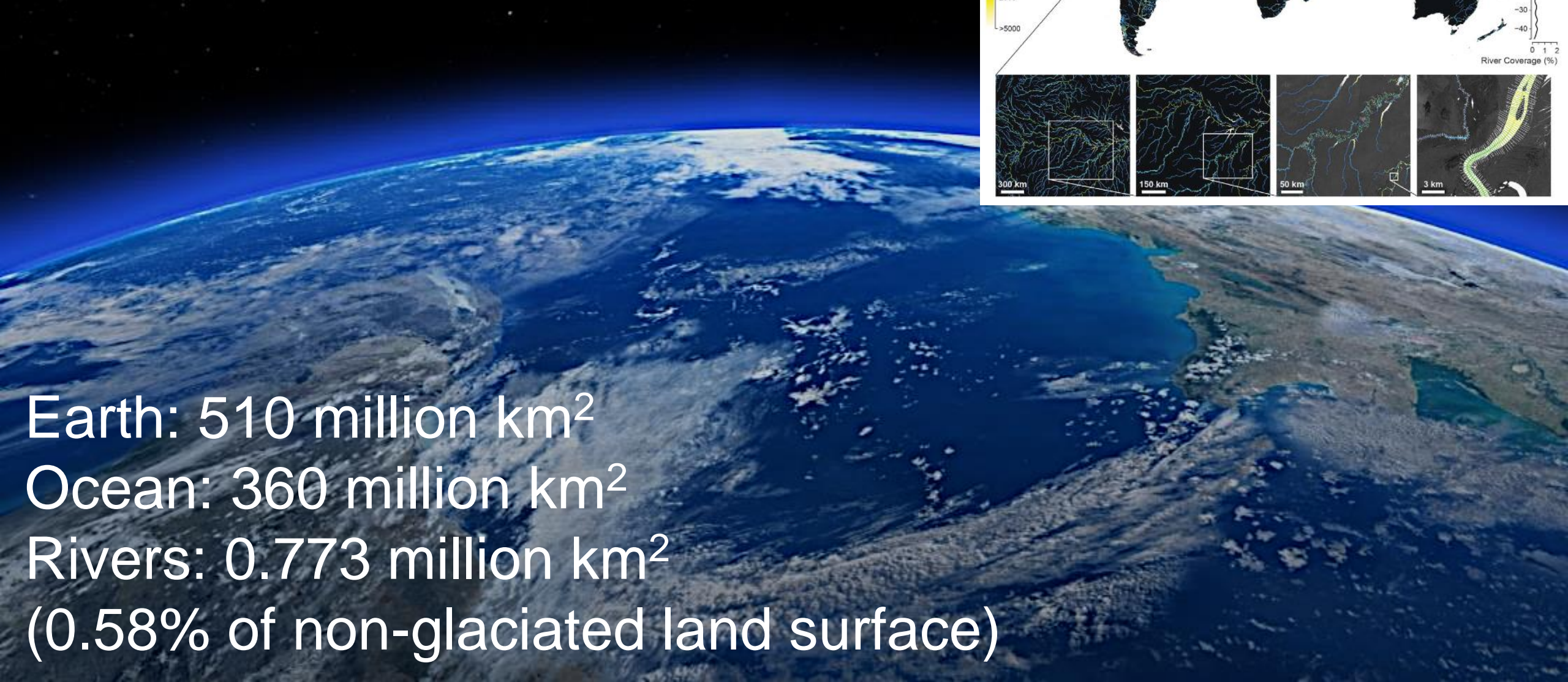
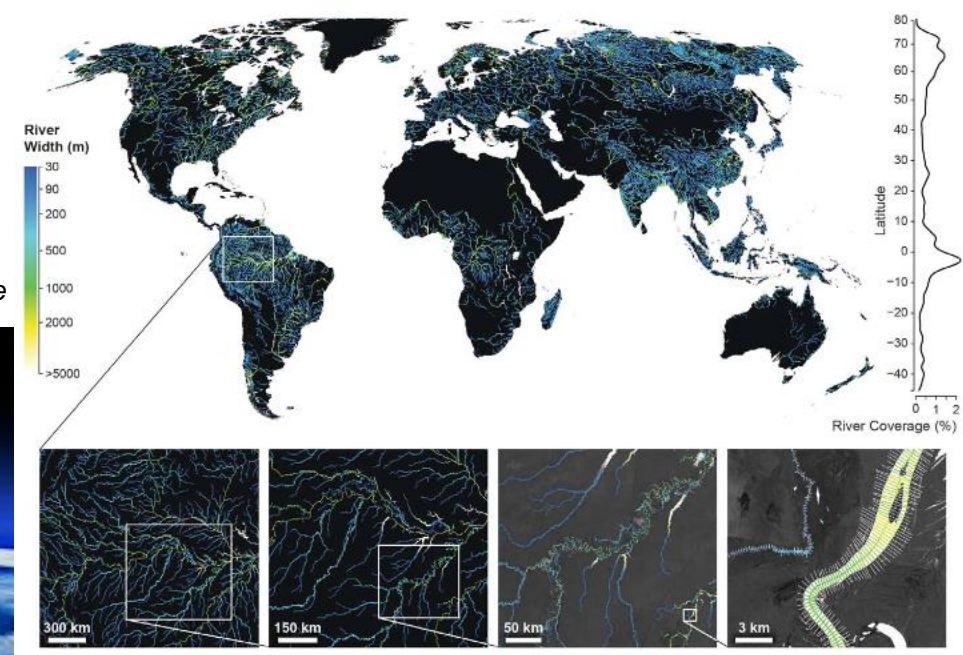
## Perception of hydrologists long shaped our understanding of rivers as ‘pipelines’

[Physical transport overwhelms biogeochemical transformations]



# Small by areal extent

*Allen & Pavelsky 2018 Science*



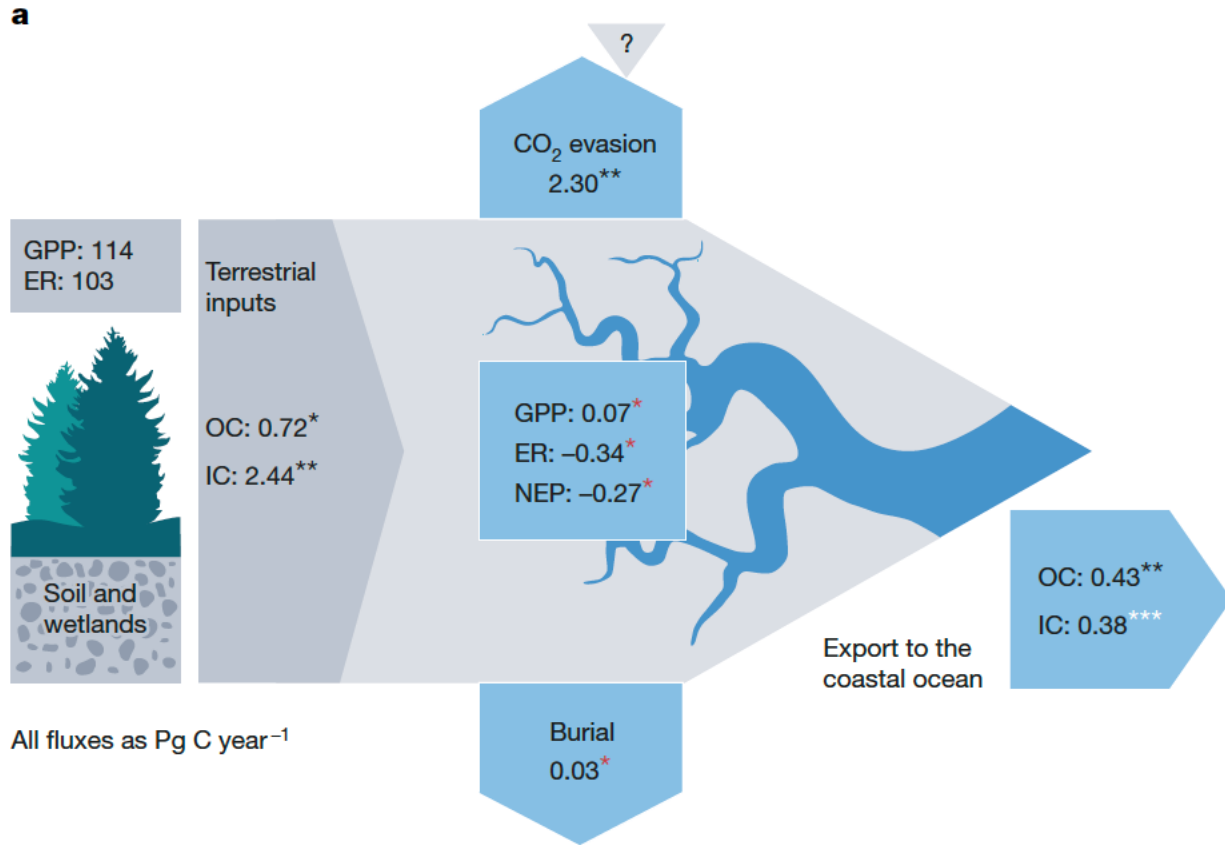
Earth: 510 million km<sup>2</sup>

Ocean: 360 million km<sup>2</sup>

Rivers: 0.773 million km<sup>2</sup>

(0.58% of non-glaciated land surface)

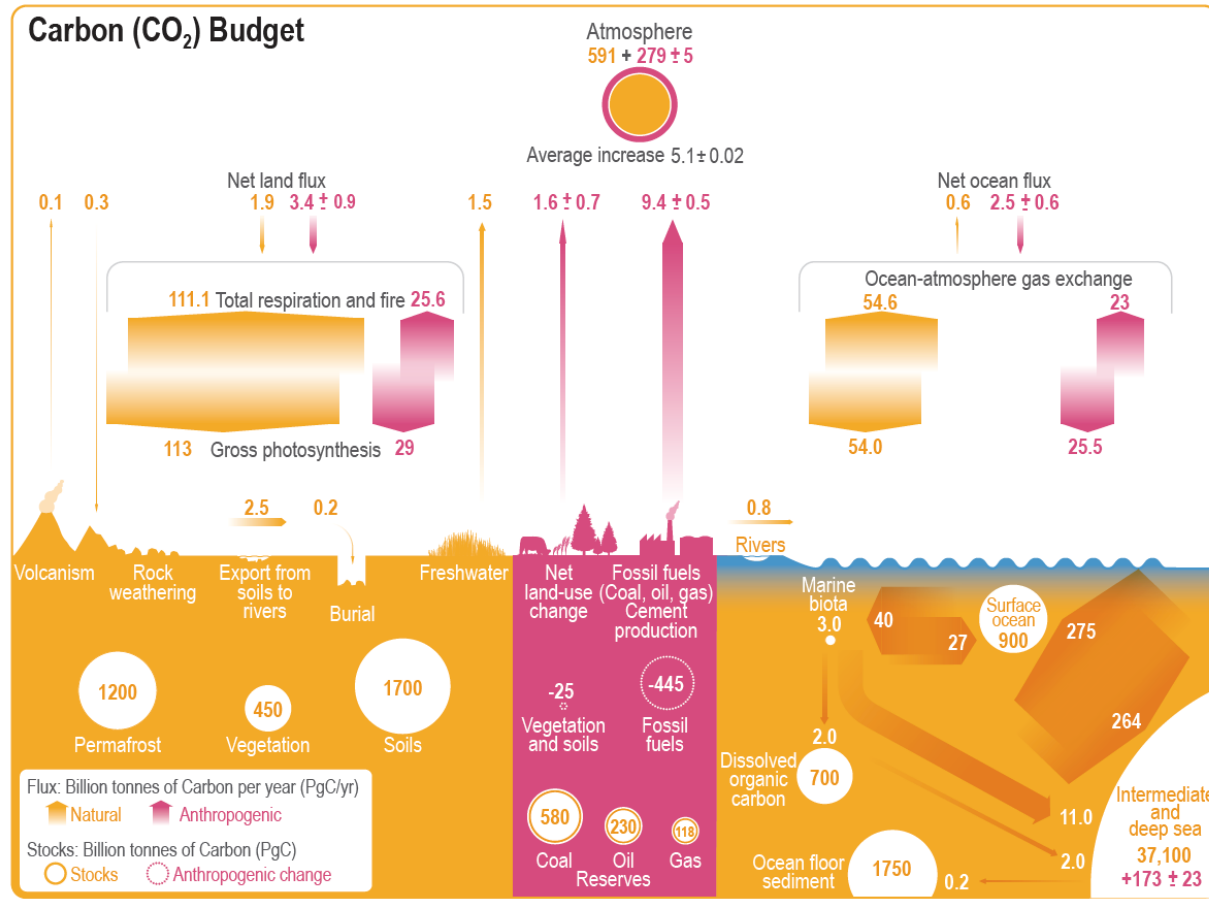
# Largest biogeochemical nexus between land, the oceans and atmosphere



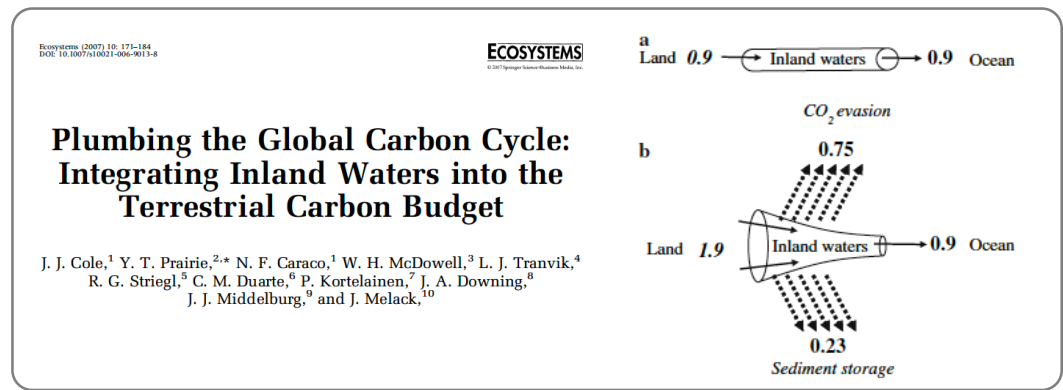
1 Gigatonne (Gt) = 1 billion tonnes =  $1 \times 10^{15}$ g = 1 Petagram (Pg)

- Rivers figure among the most heterotrophic ecosystems (that is, they respire more than they produce)
- The world's rivers are major CO<sub>2</sub> 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 CO<sub>2</sub> 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

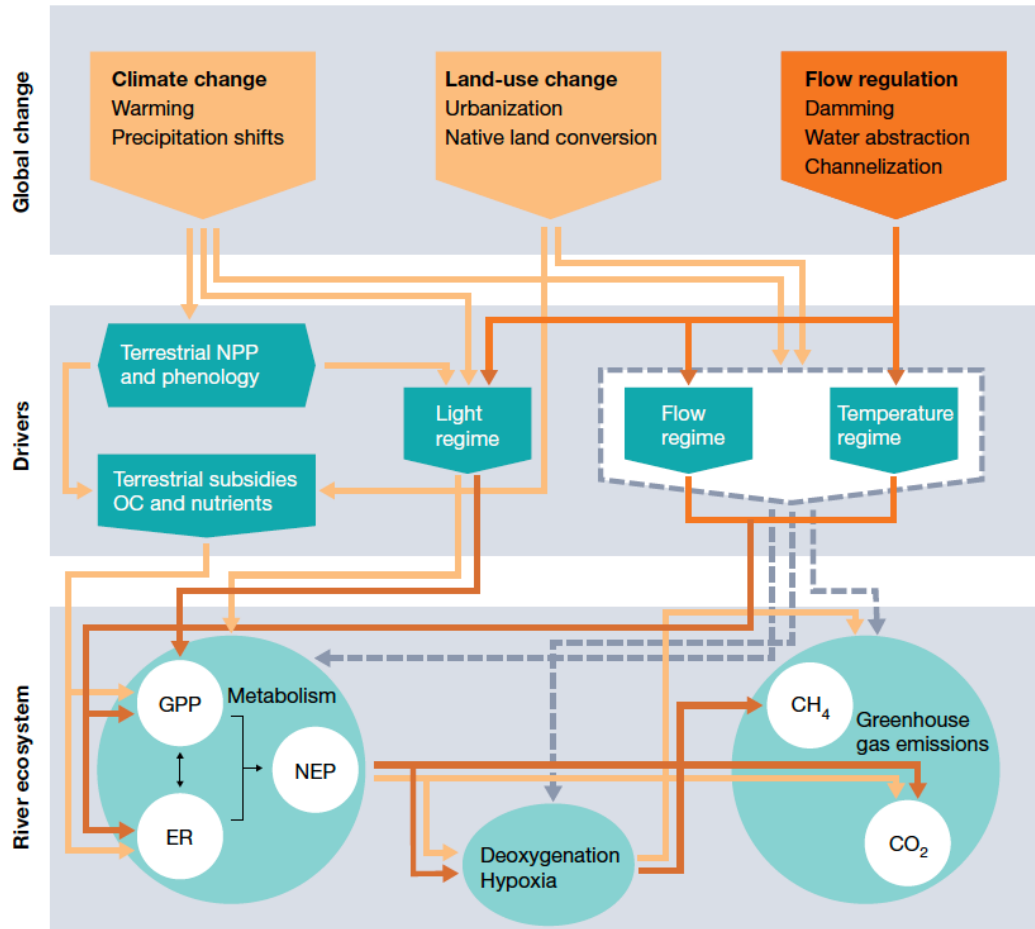


Canadell, J.G., P.M.S. Monteiro, M.H. Costa, L. Cotrim da Cunha, P.M. Cox, A.V. Eliseev, S. Henson, M. Ishii, S. Jaccard, C. Koven, A. Lohila, P.K. Patra, S. Piao, J. Rogelj, S. Syampungani, S. Zaehle, and K. Zickfeld, 2021: Global Carbon and other Biogeochemical Cycles and Feedbacks. In *Climate Change 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.



**Figure 5.12 | Global carbon (CO<sub>2</sub>) budget (2010–2019).** Yellow arrows represent annual carbon fluxes (in PgC yr<sup>-1</sup>) 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 CO<sub>2</sub>, nitrogen deposition). The adjusted gross natural ocean–atmosphere CO<sub>2</sub> flux was derived by rescaling the value in Figure 1 of Sarmiento and Gruber (2002) of 70 PgC yr<sup>-1</sup> by the revised estimate of the bomb radiocarbon (<sup>14</sup>C) inventory in the ocean. The original bomb <sup>14</sup>C inventory yielded an average global gas transfer velocity of 22 cm hr<sup>-1</sup>; the revised estimate is 17 cm hr<sup>-1</sup> 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).

# Global change, river ecosystem processes and biogeochemistry



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

Review

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

Nature | Vol 613 | 19 January 2023

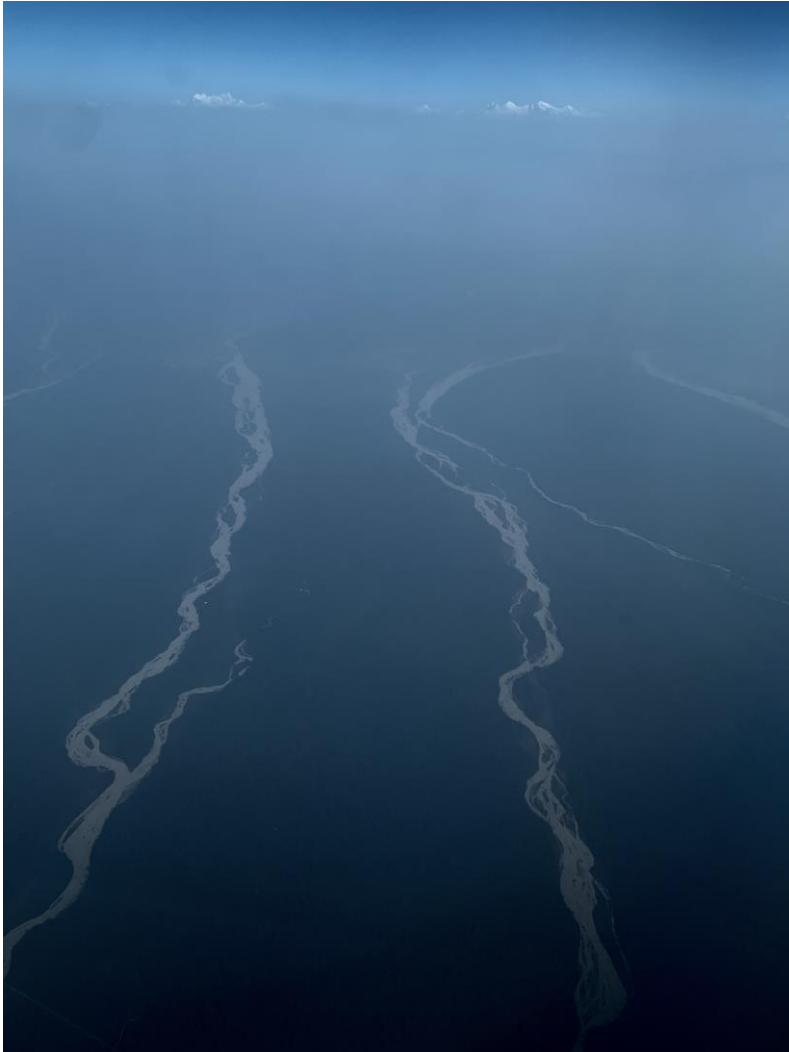
Mountains account for 25% of Earth's land surface and their streams contribute more than 30% to global runoff.

Mountains are highly vulnerable to climate change.

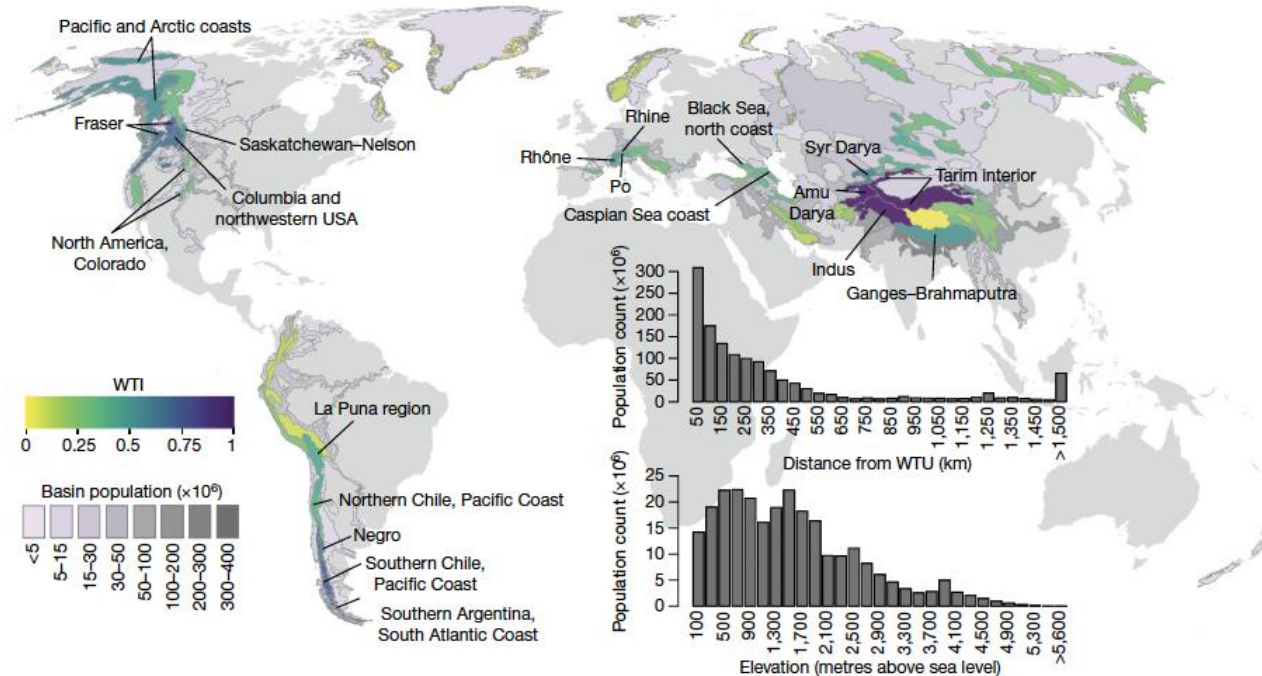


# Consequences of melting mountain glaciers

## Vanishing water towers



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



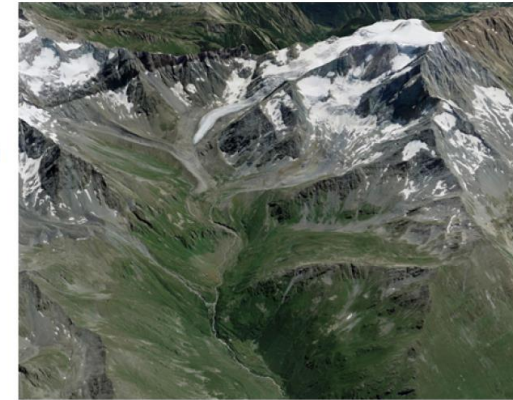
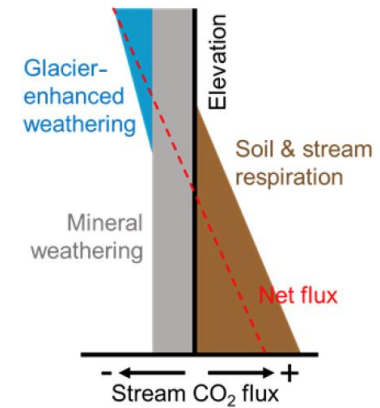
Immerzeel et al. 2029 Nature

# Taking the 'heartbeat' of glacier-fed streams

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



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

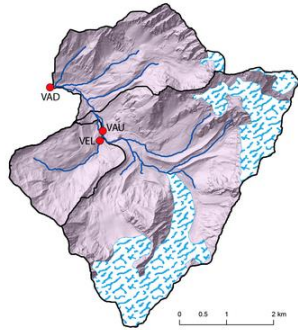


# Taking the 'heartbeat' of glacier-fed streams

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

## Our Study Sites

Explore our stations and their catchments

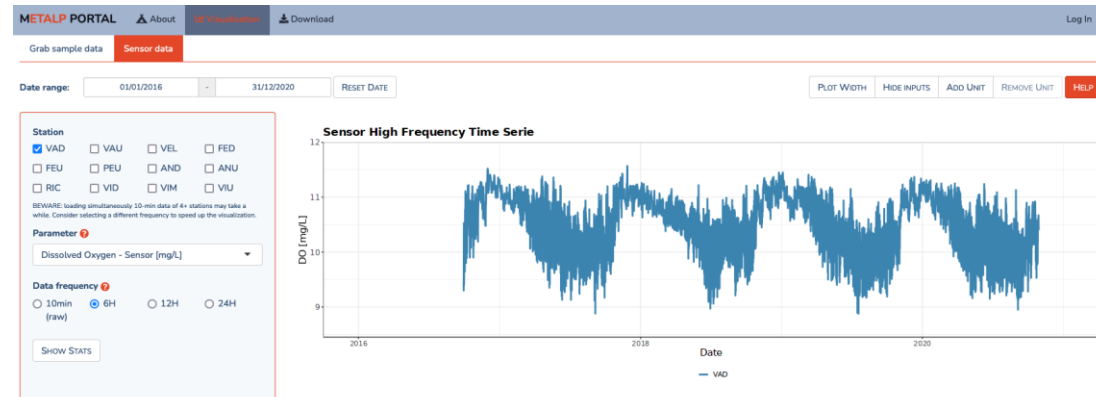
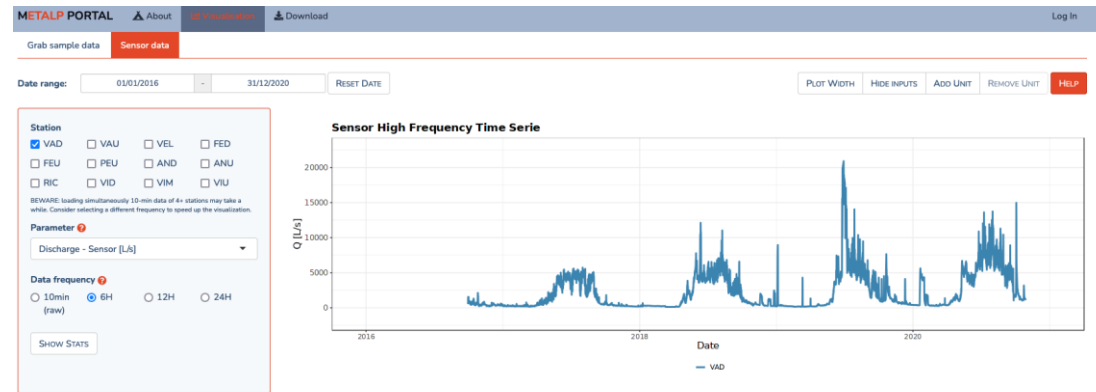
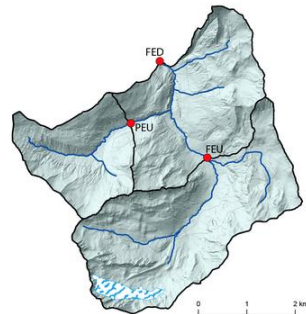


Valsorey catchment

|                         | TORRENT DU VALSOREY<br>DOWNSTREAM | TORRENT DU VALSOREY<br>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 [km <sup>2</sup> ] | 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<br>DOWNSTREAM | DRANSE DE FERRET<br>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 <sup>2</sup> ] | 20.24                          | 9.33                         | 3.97      |
| Vegetated area [%]      | 50.07                          | 39.60                        | 61.19     |
| Glacier coverage [%]    | 1.78                           | 3.86                         | 0         |





# Consequences of melting glaciers

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

# Cruising the roof of our planet



# An amazing 'field team'

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

Reportage



# 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.

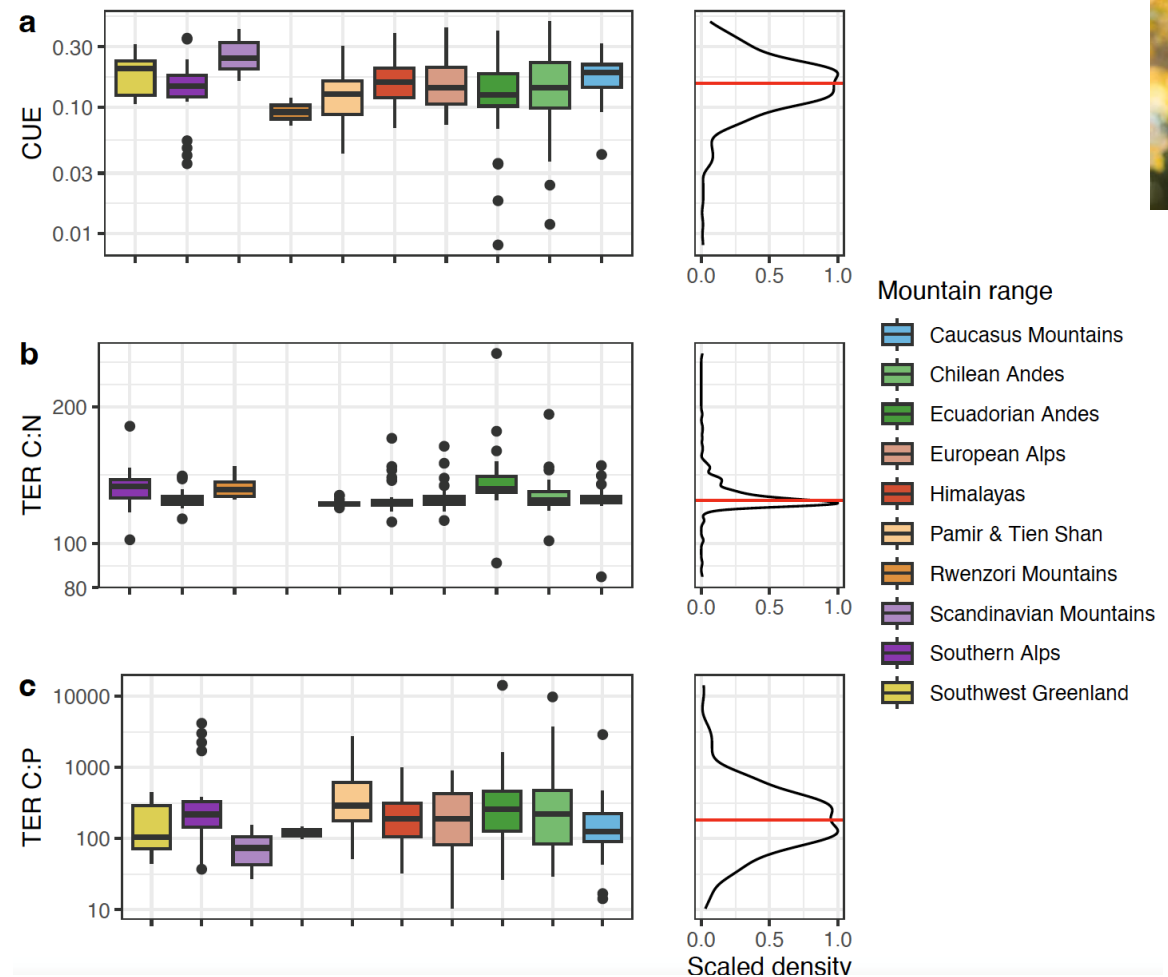
# Glacier-fed streams

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)



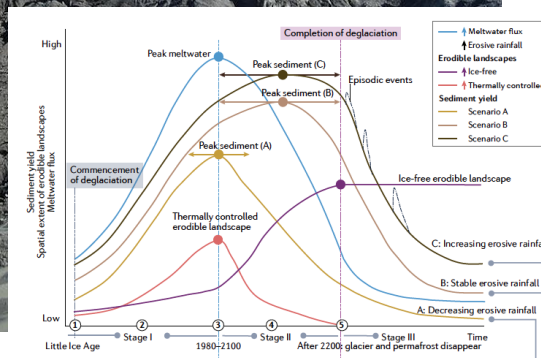
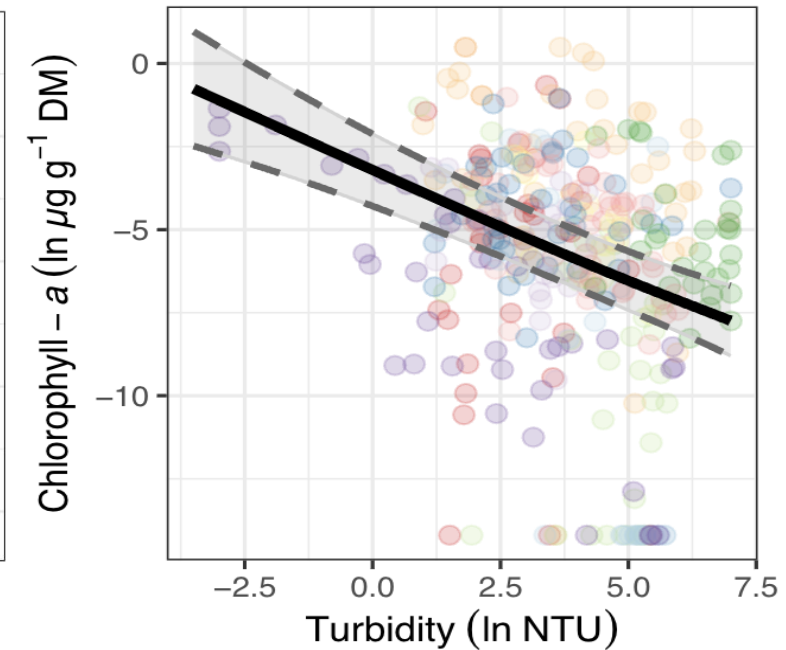
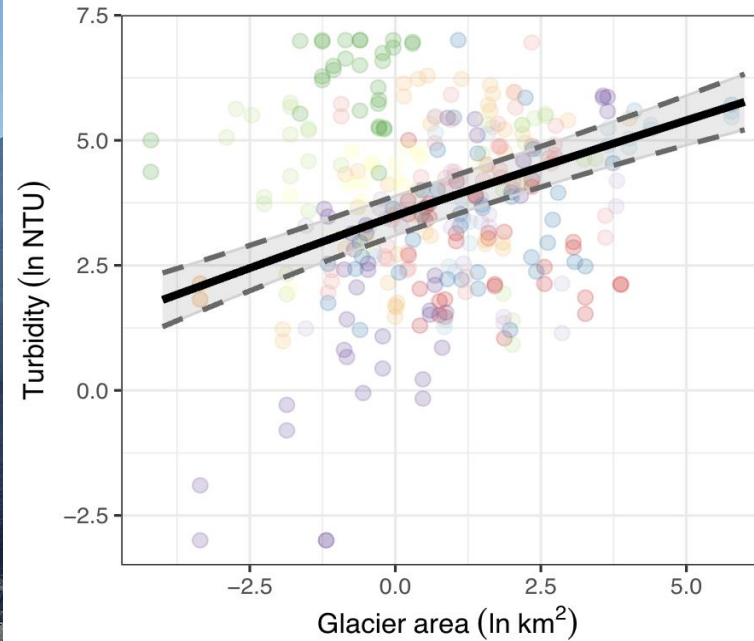
# Resource limitation and microbial starvation



- 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



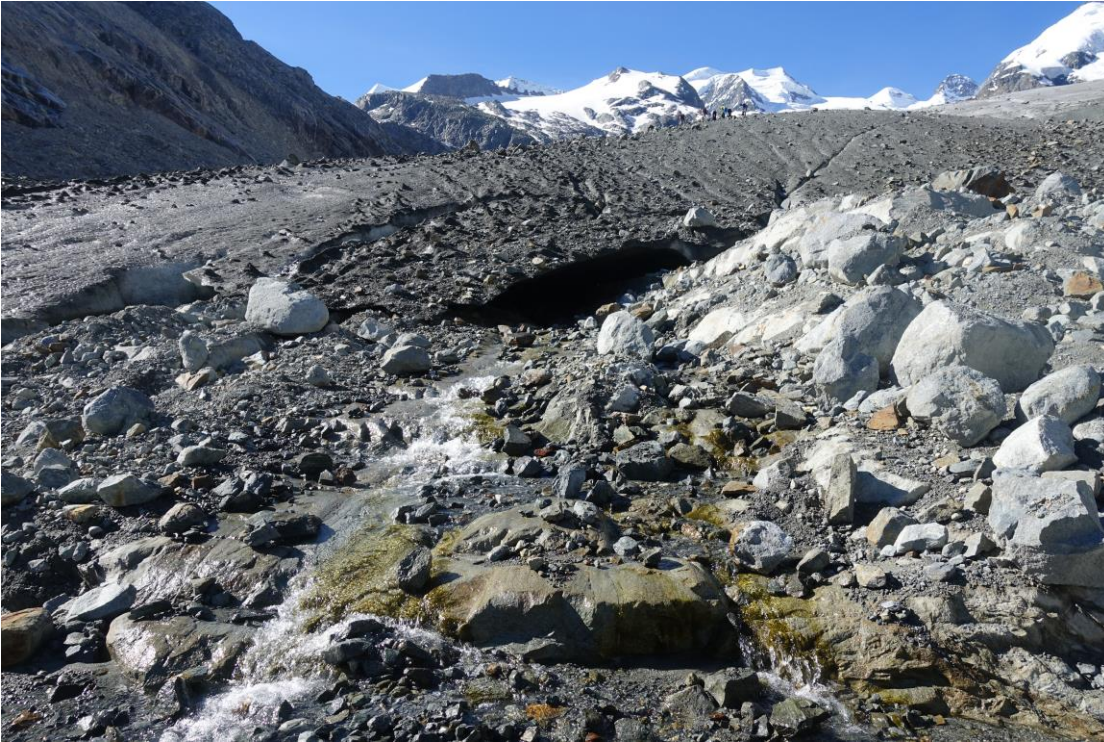
Global trends indicate:

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

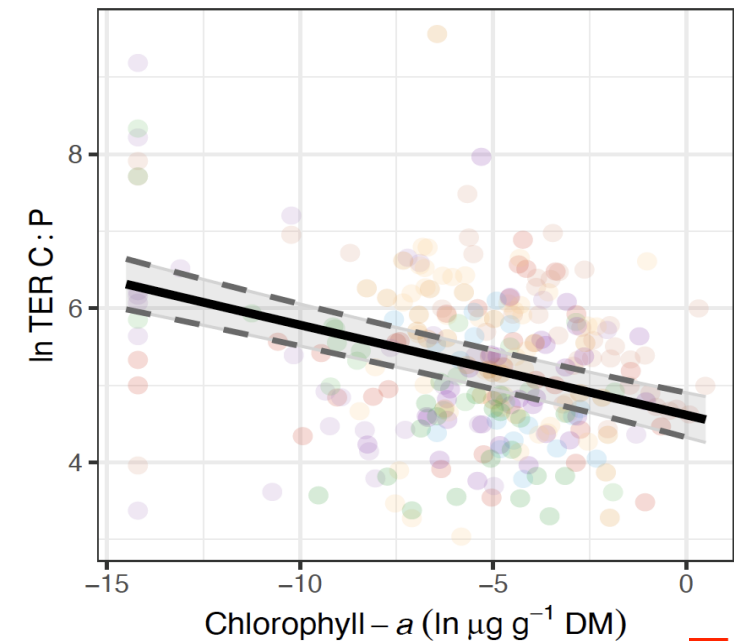
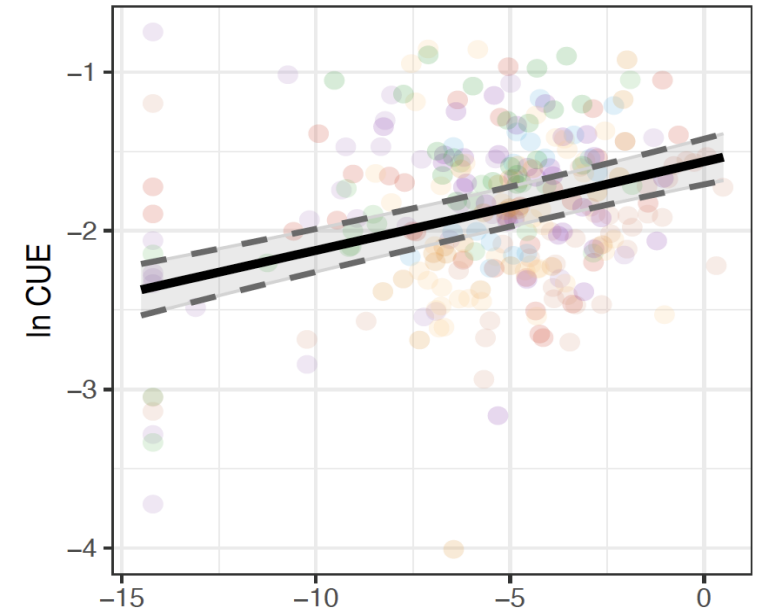
Kohler et al. 2024 Nature Geoscience

Bourquin et al. (2025) Nature Communications

# 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 efficiency — relatively more organic carbon allocated to biomass growth



# TAKE HOME PART 1

- 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
- As glaciers melt, the environment of glacier-fed streams changes dramatically
- Transitional ecosystems — undergoing major environmental and biogeochemical shifts
- Changing microbial energetics and ecosystem functioning



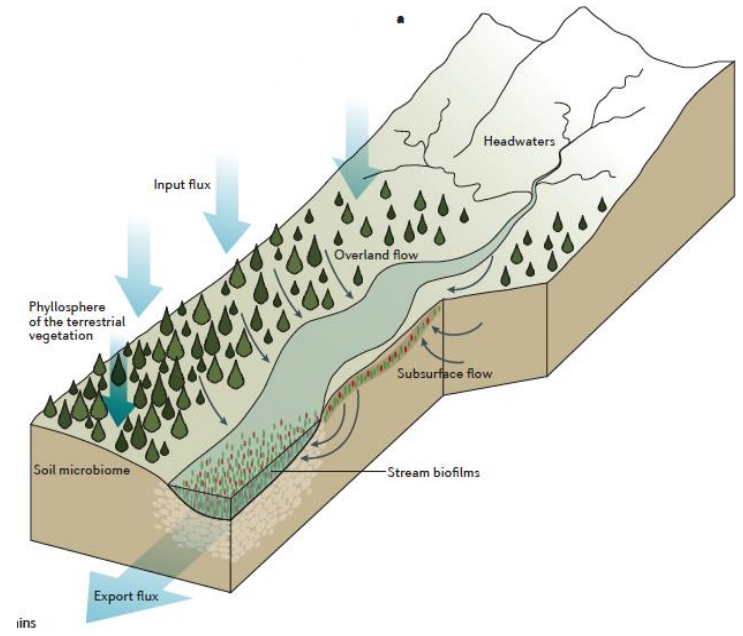
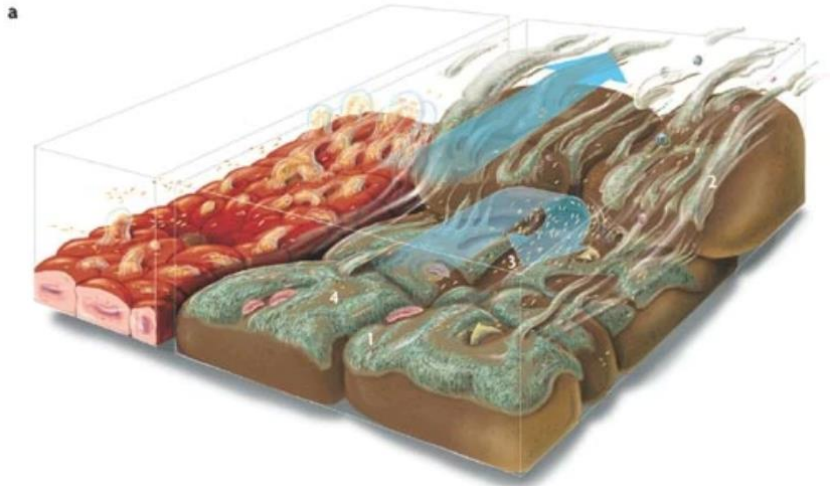
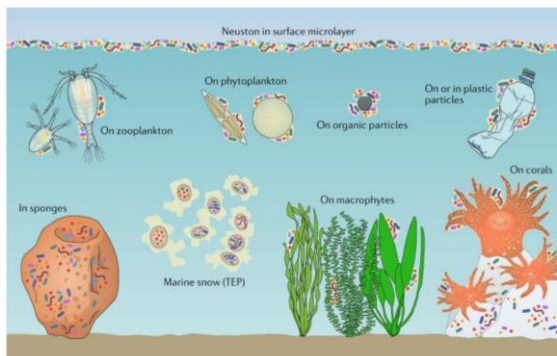
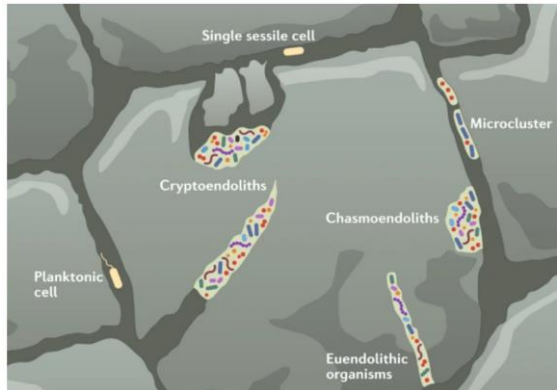
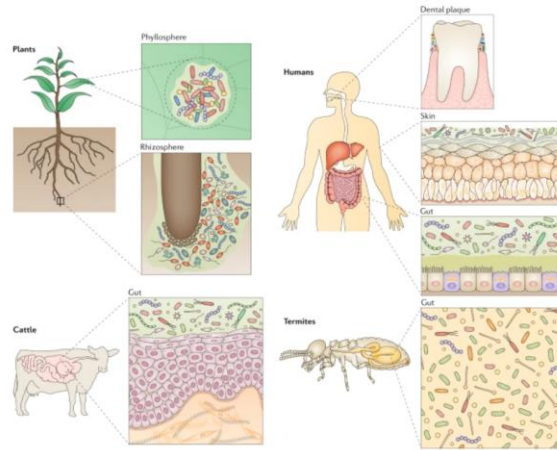
<https://www.glacierstreams.ch/>  
<https://www.epfl.ch/labs/river/>

# Microbial biofilms



# Microbial biofilms

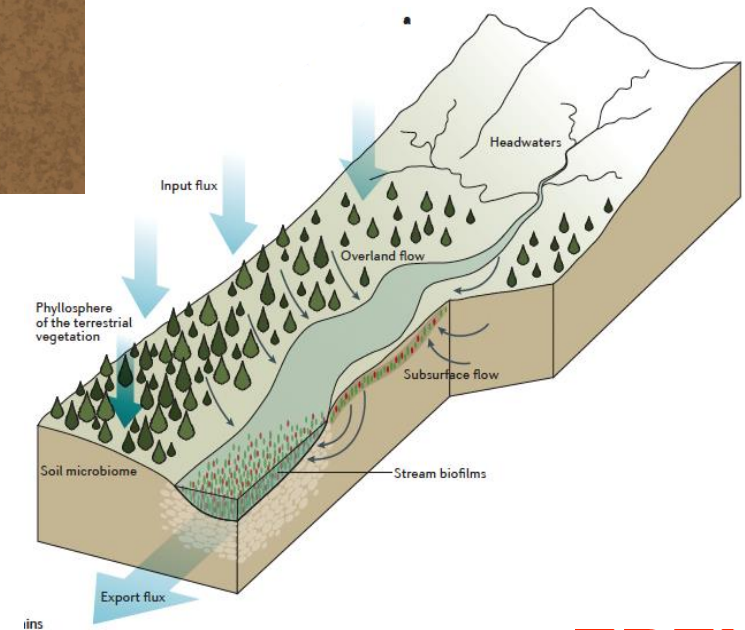
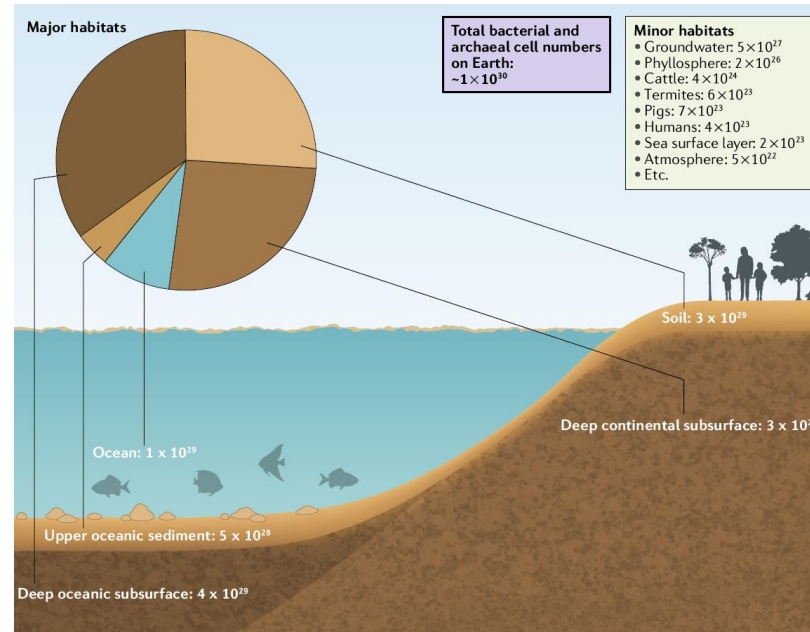
Most successful form of life over 3.2 billion years



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

# Most microbes live attached to surfaces!

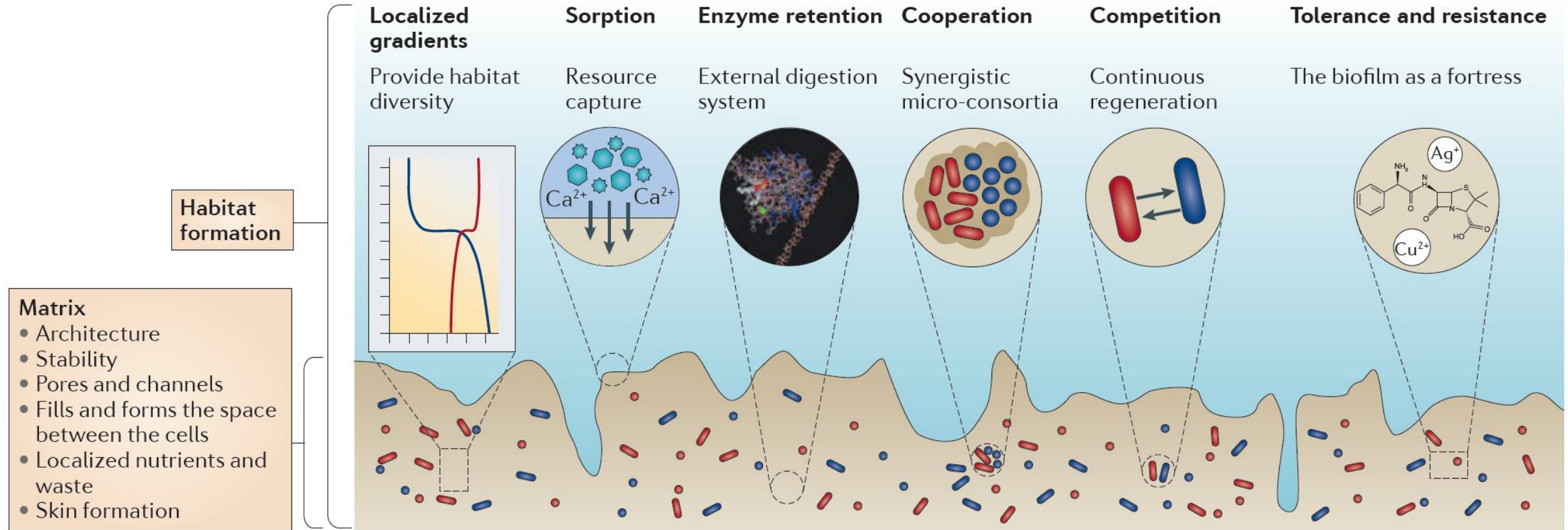
| Habitat                                       | Estimated total (bacterial and archaeal) cell number <sup>a</sup> | Estimated cell number in biofilms <sup>b</sup>  |
|---|---|---|
| Total Earth                                   | $1.2 \times 10^{30}$  | On surface of Earth: $3.5 \times 10^{29}$ ; deep subsurface: large but as yet unknown, ranging from $4.9 \times 10^{29}$ to $9.1 \times 10^{29}$                      |
| Deep oceanic subsurface <sup>c</sup>          | $4 \times 10^{29}$  | Most cells attached, either single or in clusters; 20–80% in biofilms based on microscopic and biogeochemical evidence  |
| Deep continental subsurface <sup>d</sup>      | $3 \times 10^{29}$  | Most cells attached, single and microclusters; 20–80% in biofilms based on microscopic and biogeochemical evidence  |
| Top 10–50 cm of oceanic sediment <sup>e</sup> | $5 \times 10^{28}$  | $5 \times 10^{28}$  |
| Soil  | $3 \times 10^{29}$  | $3 \times 10^{29}$  |
| Open ocean                                    | $1 \times 10^{29}$  | Large planktonic fraction, unknown numbers in marine snow, transparent exopolymer particles, gels, on mineral and debris particles, microplastics, plants and animals |
| Groundwater                                   | $5 \times 10^{27}$  | Unattached  |
| Atmosphere <sup>f</sup>                       | $5 \times 10^{22}$  | Unknown but unlikely  |



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

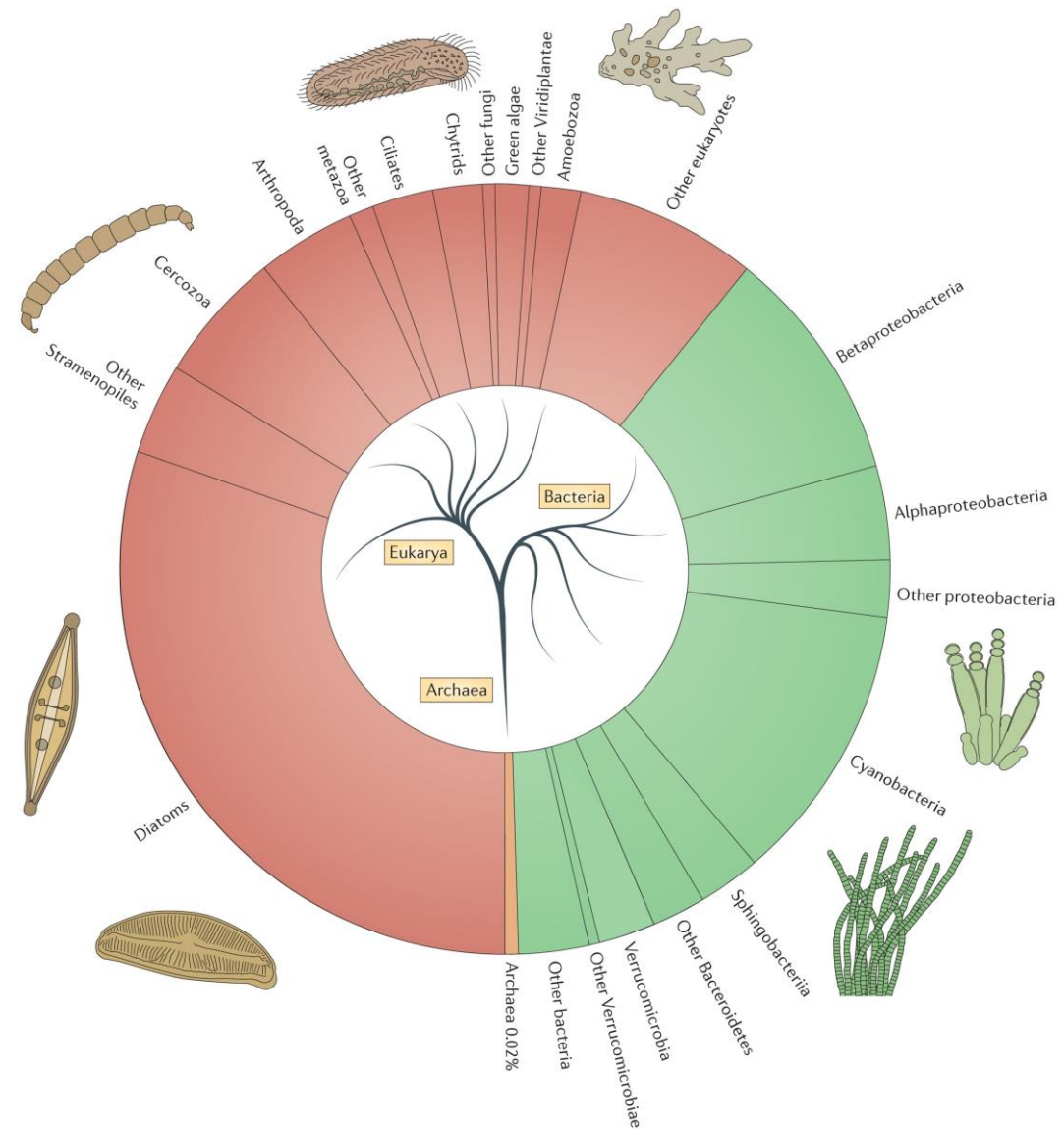
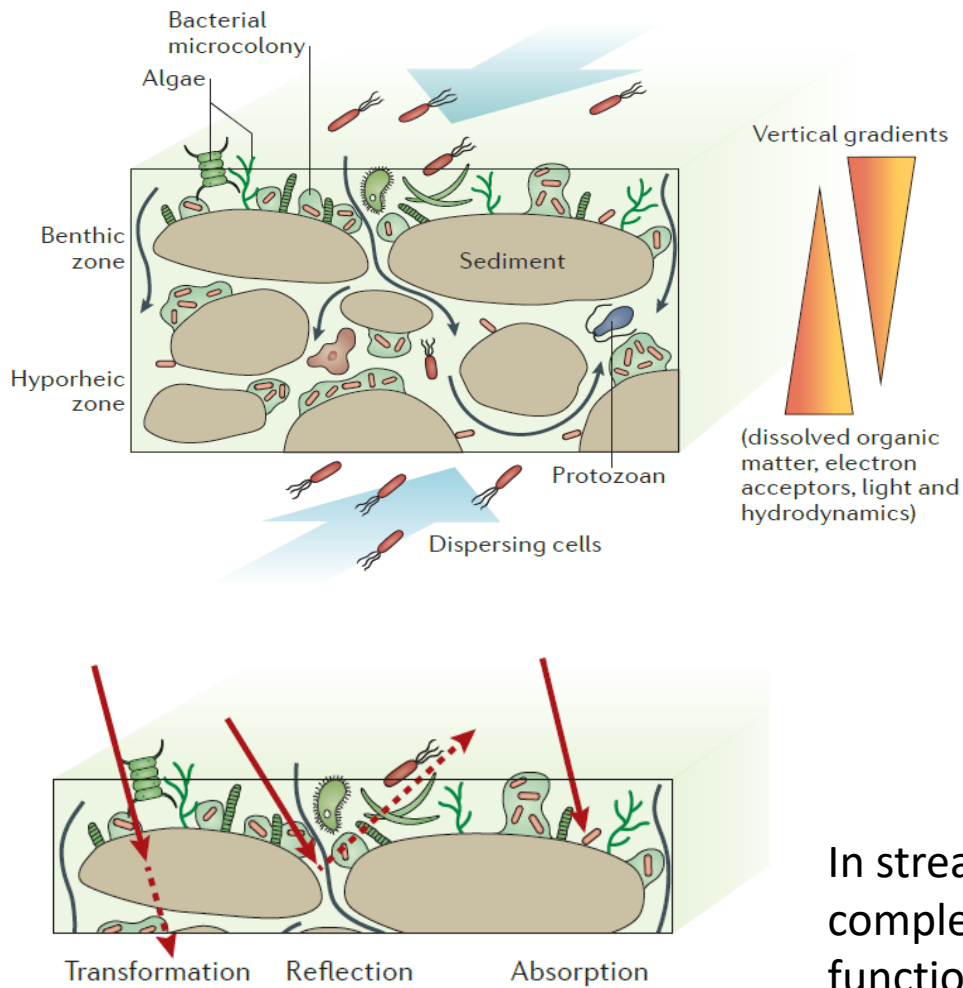
# Biofilms: an emergent form of bacterial life

Hans-Curt Flemming<sup>1</sup>, Jost Wingender<sup>1</sup>, Ulrich Szewzyk<sup>2</sup>, Peter Steinberg<sup>3</sup>, Scott A. Rice<sup>4</sup> and Staffan Kjelleberg<sup>4</sup>



# The ecology and biogeochemistry of stream biofilms

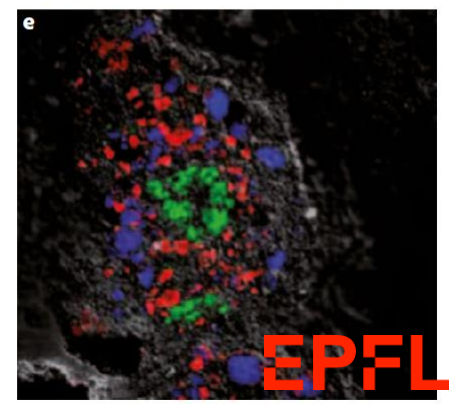
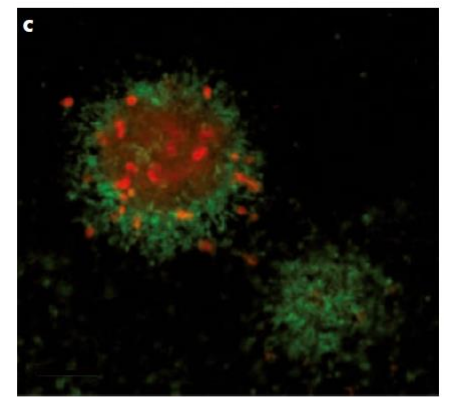
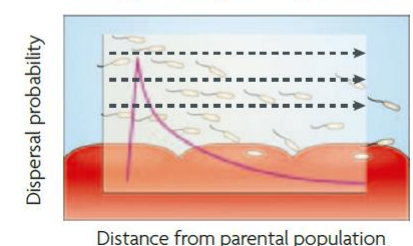
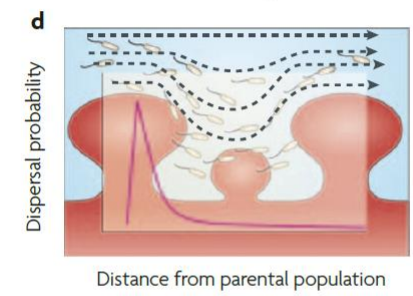
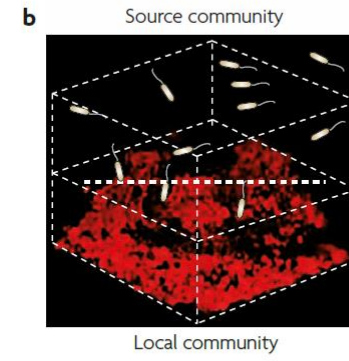
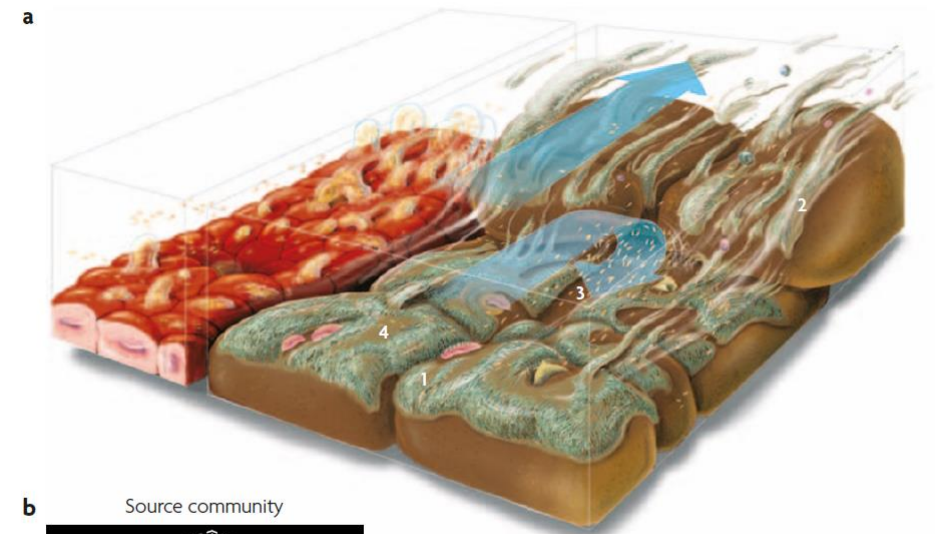
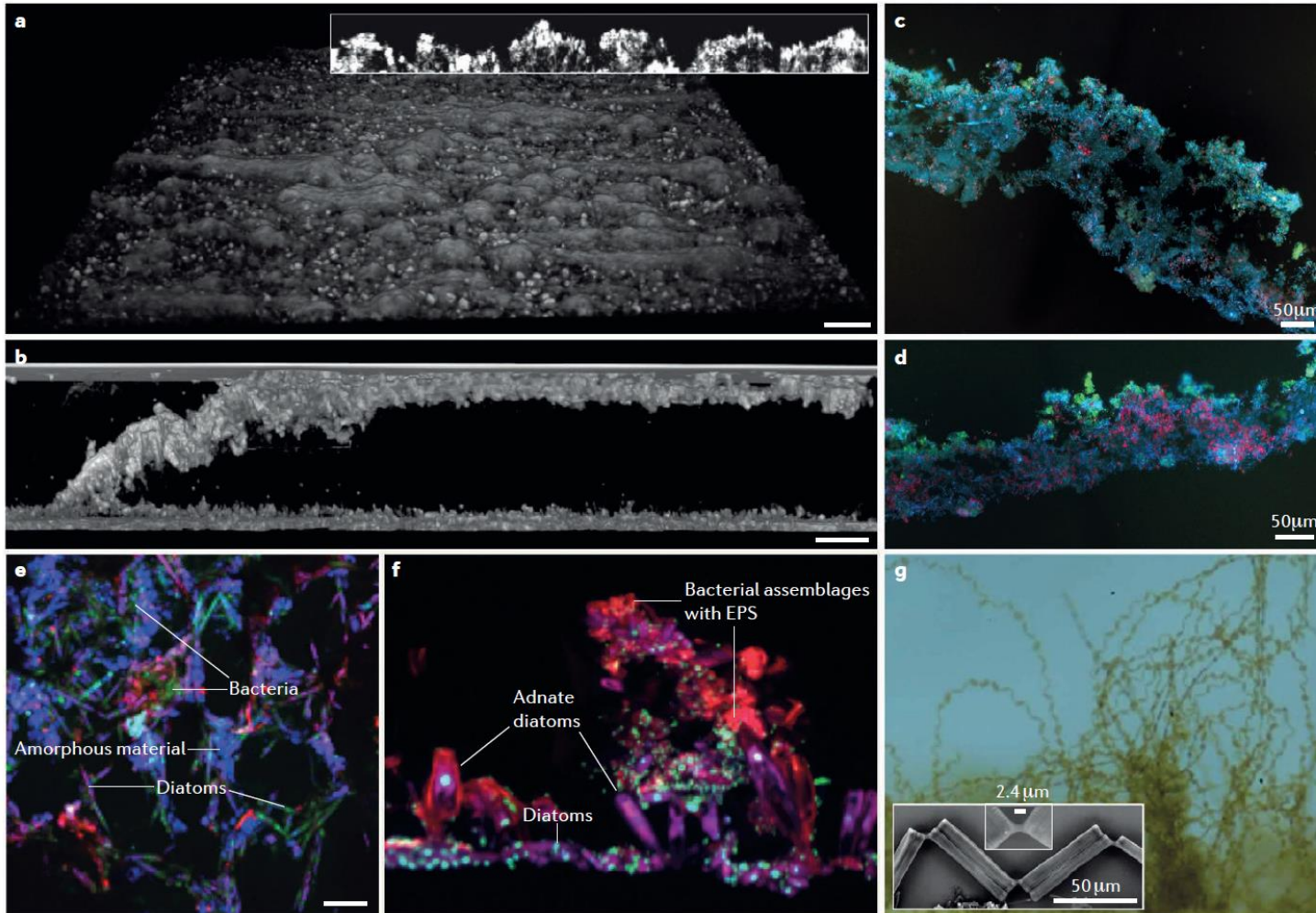
Tom J. Battin<sup>1</sup>, Katharina Besemer<sup>2</sup>, Mia M. Bengtsson<sup>3</sup>, Anna M. Romani<sup>4</sup> and Aaron I. Packmann<sup>5</sup>



In streams and rivers, biofilm communities are highly complex /diverse and perform important ecosystem functions (e.g. metabolism, water purification, retention of nutrients, cycling of elements, ...)

# Microbial landscapes: new paths to biofilm research

Tom J. Battin, William T. Sloan, Staffan Kjelleberg, Holger Daims, Ian M. Head, Tom P. Curtis and Leo Eberl

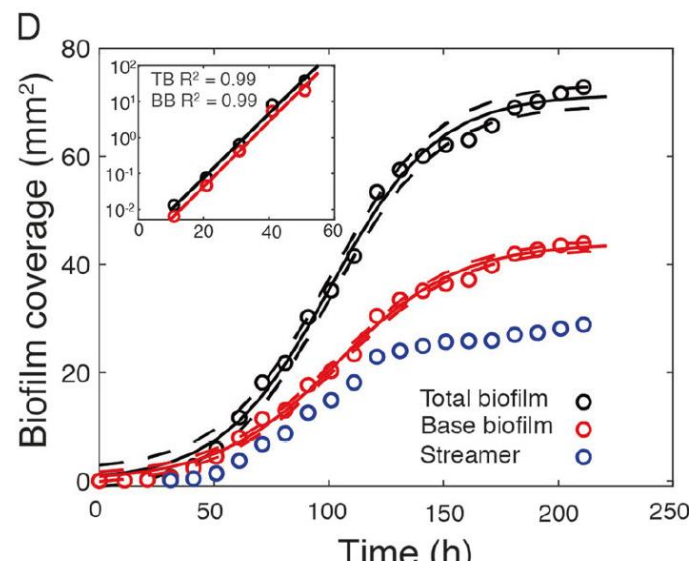
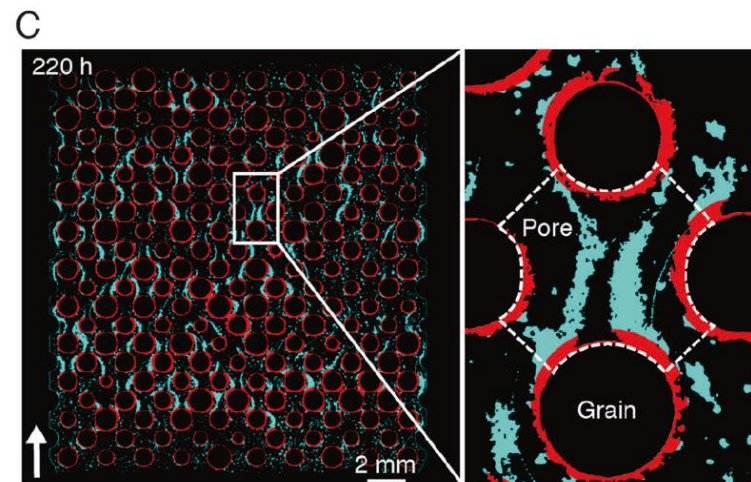
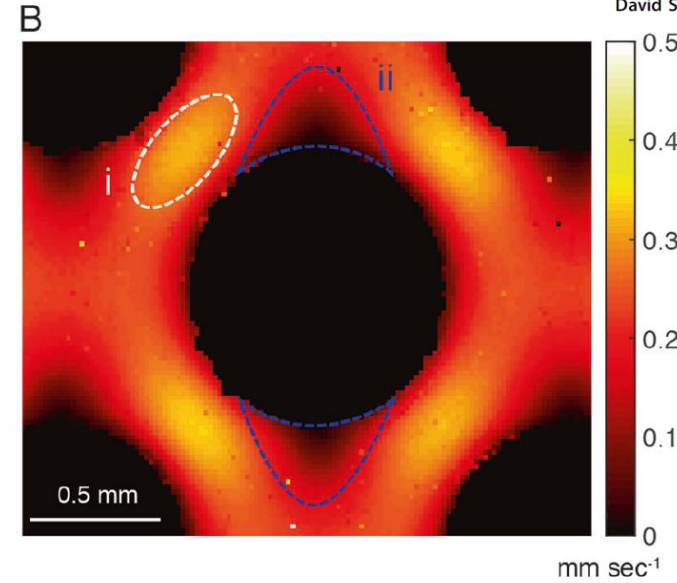
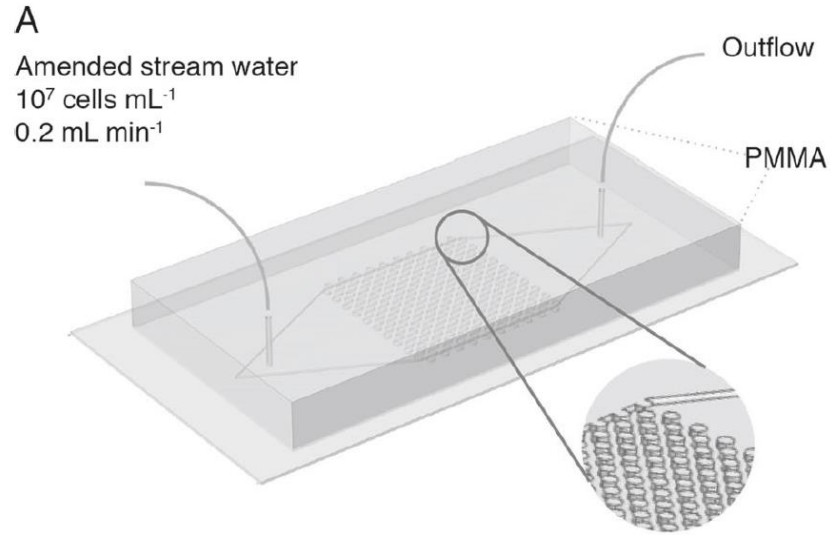


# the small scale...



## Unraveling the biophysical underpinnings to the success of multispecies biofilms in porous environments

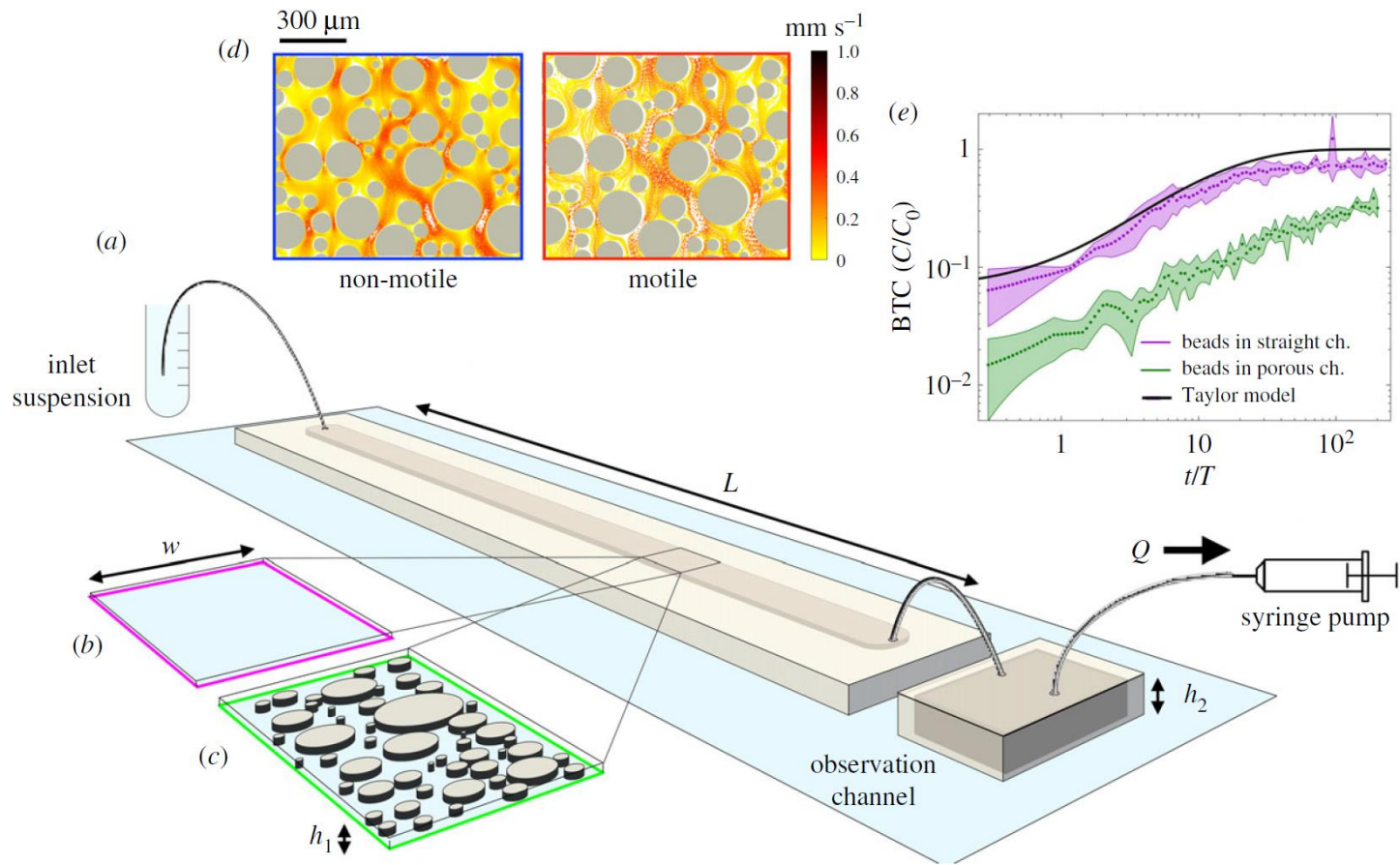
David Scheidweiler<sup>1</sup> · Hannes Peter<sup>1</sup> · Paraskevi Pramateftaki<sup>1</sup> · Pietro de Anna<sup>2</sup> · Tom J. Battin<sup>1</sup>



Microfluidics is a powerful tool to study biofilms under controlled conditions.

Biofilm structure (e.g. streamer formation) can help microbes colonize porous substrates.

Architectural plasticity allows a maximization of carrying capacity.



Biofilm colonization can enhance/lead to the formation of preferential flow paths in porous environments.

Motile bacteria can escape these trajectories

## INTERFACE

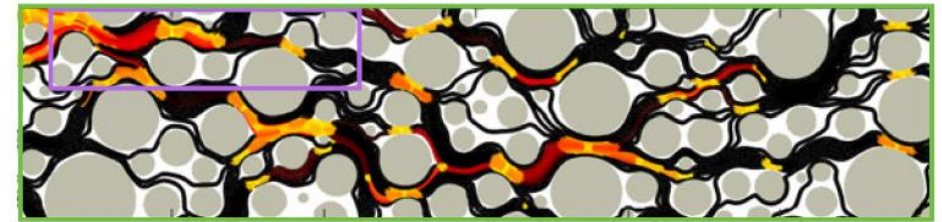
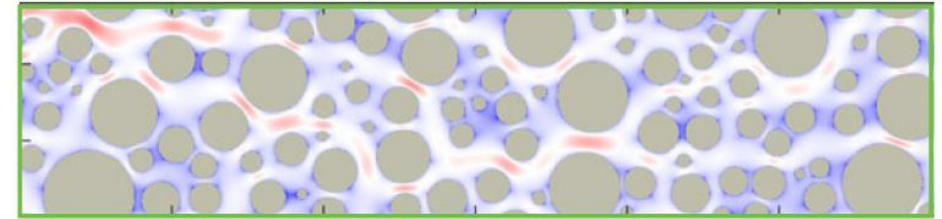
royalsocietypublishing.org/journal/rsif

## Trait-specific dispersal of bacteria in heterogeneous porous environments: from pore to porous medium scale

Research



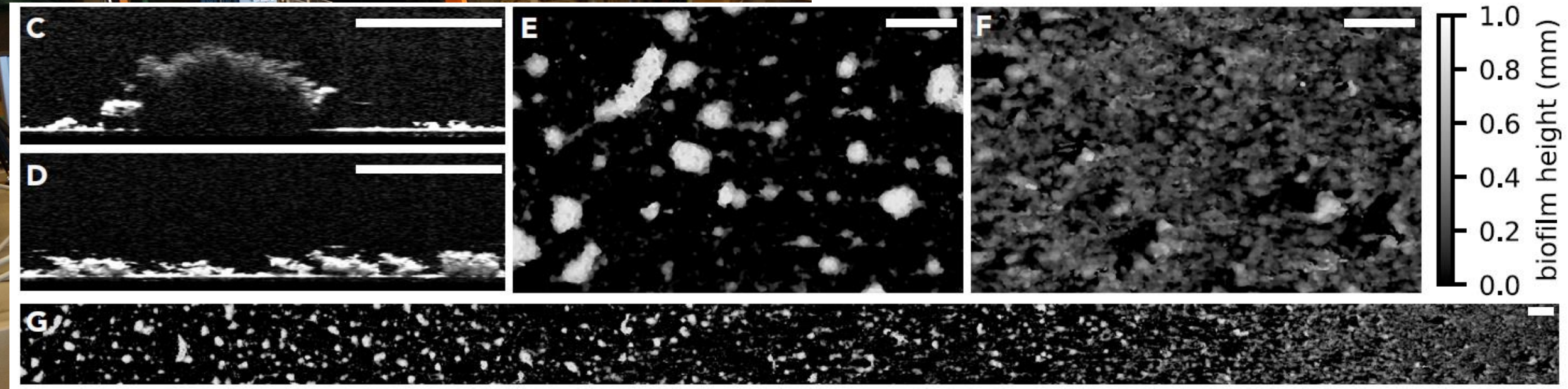
David Scheidweiler<sup>1,2</sup>, Filippo Miele<sup>2</sup>, Hannes Peter<sup>1</sup>, Tom J. Battin<sup>1</sup> and Pietro de Anna<sup>2</sup>





Article  
Morphogenesis and oxygen dynamics  
in phototrophic biofilms growing  
across a gradient of hydraulic conditions

Anna Depetris,<sup>1</sup> Hannes Peter,<sup>1</sup> Ankur Deep Bordoloi,<sup>2</sup> Hippolyte Bernard,<sup>1</sup> Amin Niayifar,<sup>1</sup> Michael Kühl,<sup>3</sup> Pietro de Anna,<sup>2</sup> and Tom Jan Battin<sup>1,4,\*</sup>

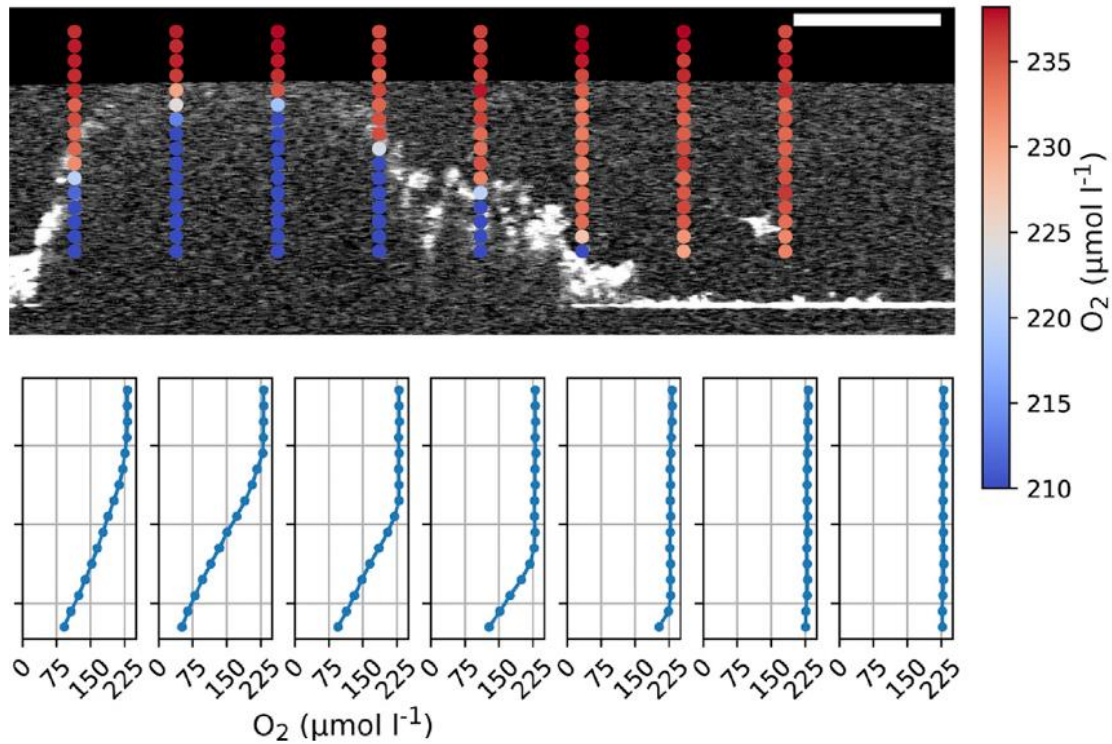


Interactions between biofilm structure  
and small-scale hydraulics lead to  
different biofilm morphologies

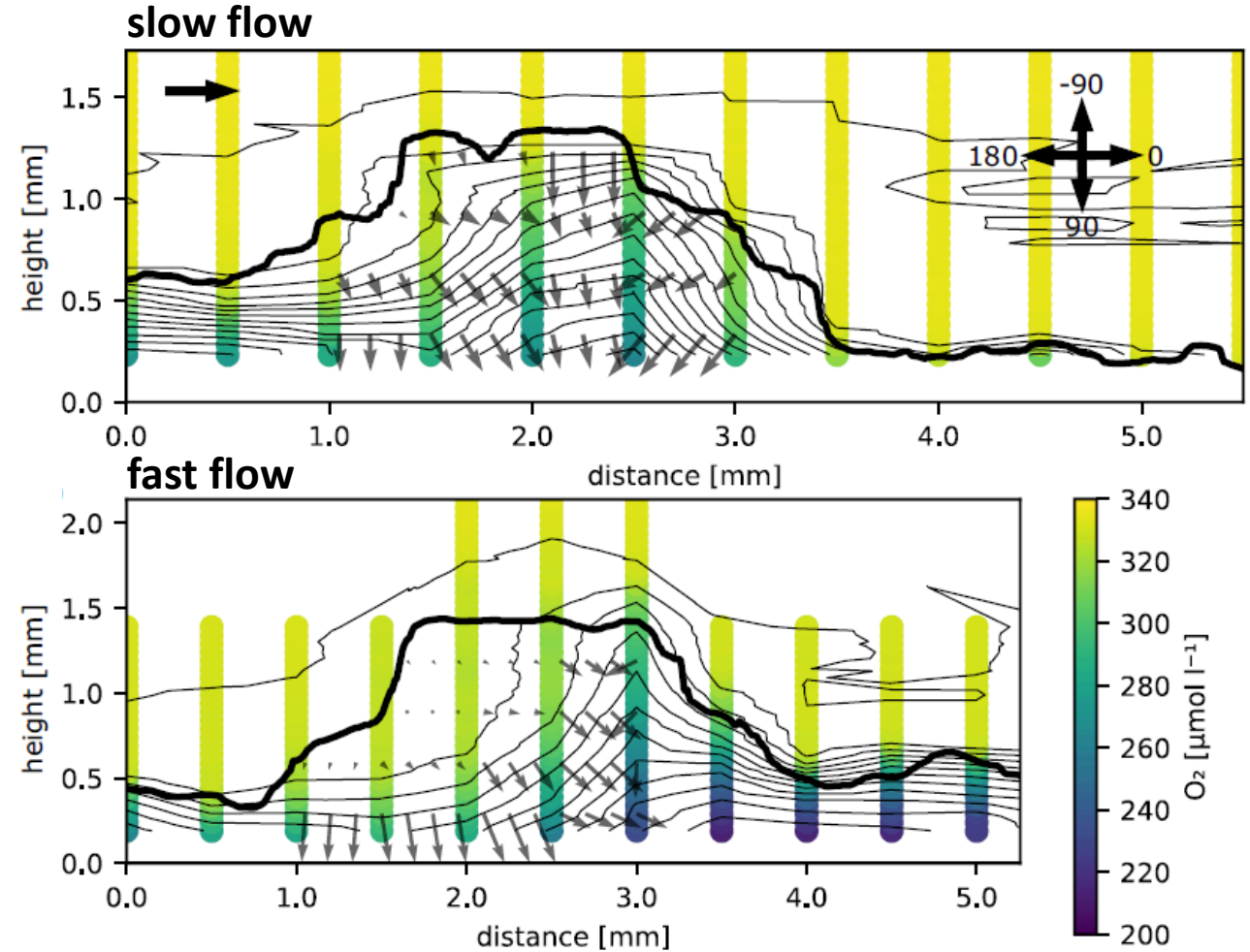
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## Biophysical properties at patch scale shape the metabolism of biofilm landscapes

Anna Depetris<sup>1</sup>, Giorgia Tagliavini<sup>1,2,3</sup>, Hannes Peter<sup>1</sup>, Michael Kühl<sup>1,4</sup>, Markus Holzner<sup>2,3</sup> and Tom J. Battin<sup>1,5</sup>

Biofilm morphology, local hydraulics and the diffusion of oxygen shape the micro-meter scale 3D structure of complex phototrophic biofilms.



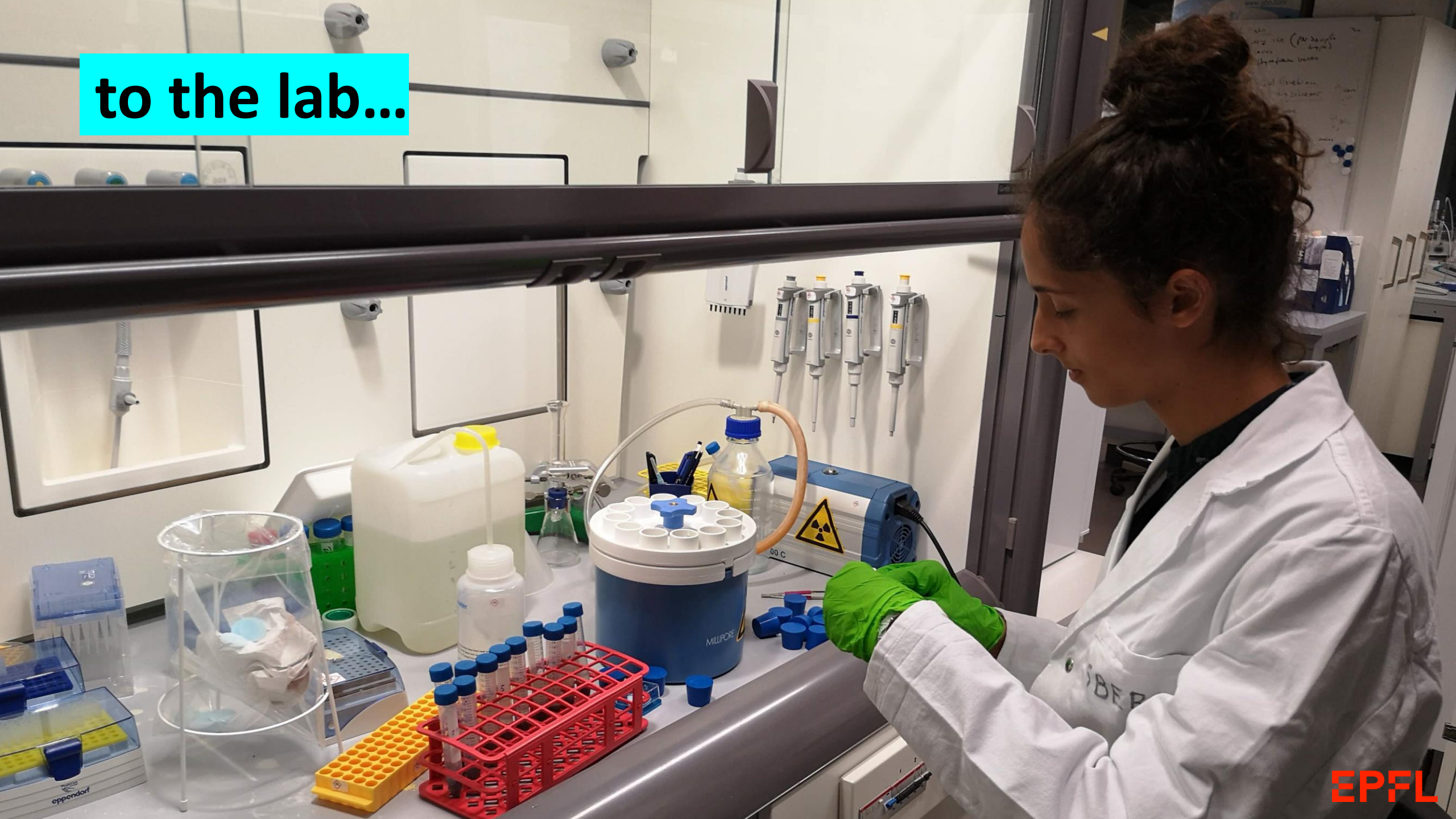
# the ecosystem scale



**from the field...**



to the lab...



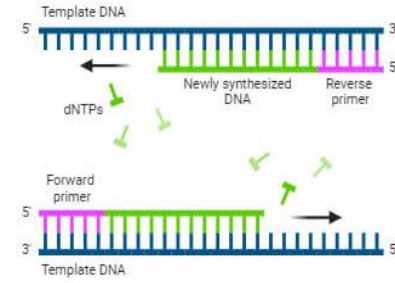
**to the computer...**



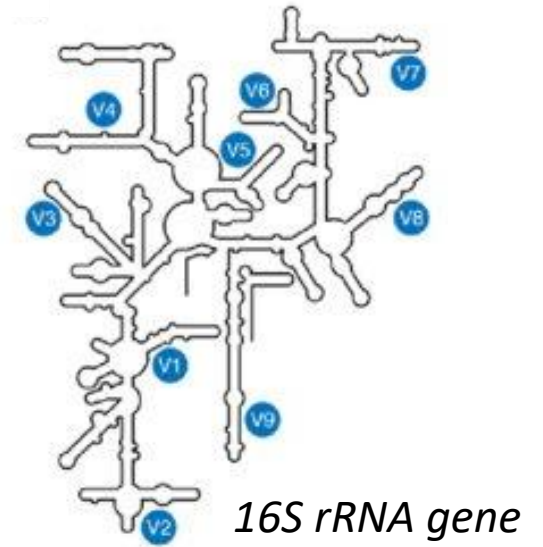
# 16S rRNA Gene Sequencing



Sample → DNA Extraction



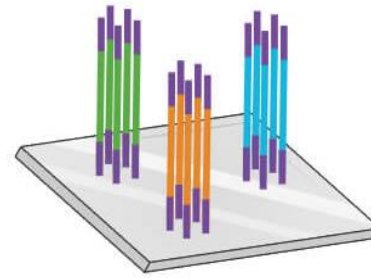
PCR



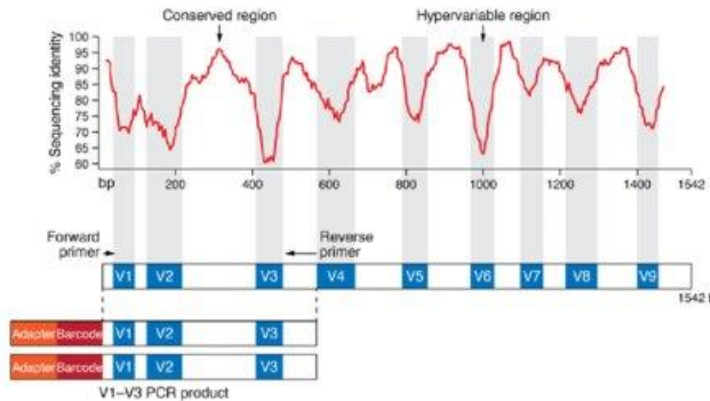
Data Analysis



DNA Sequencing



DNA Library Construction



# Global diversity and biogeography of the glacier-fed stream bacterial microbiome

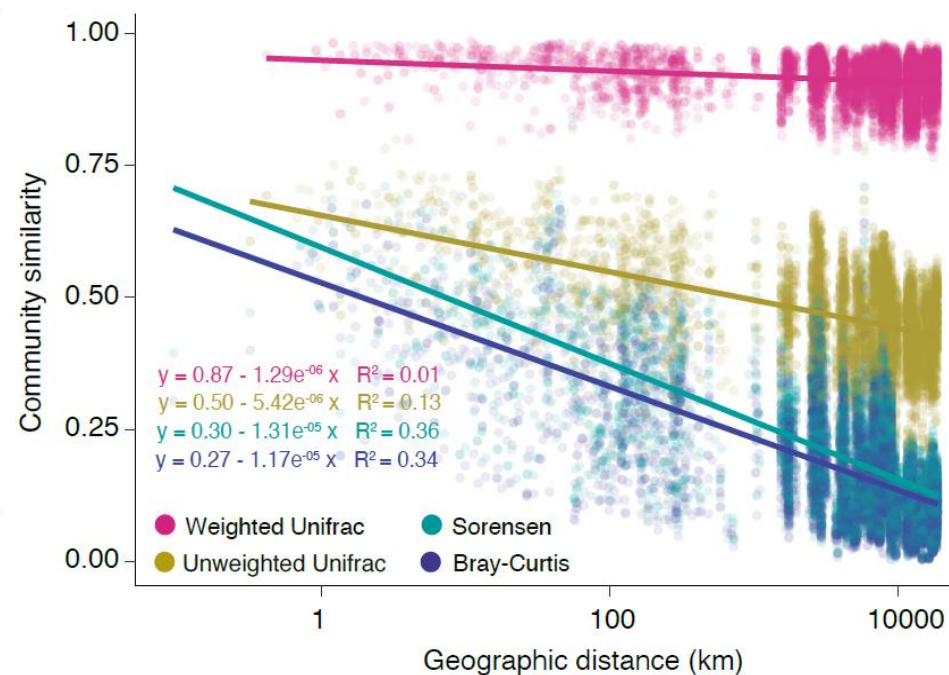
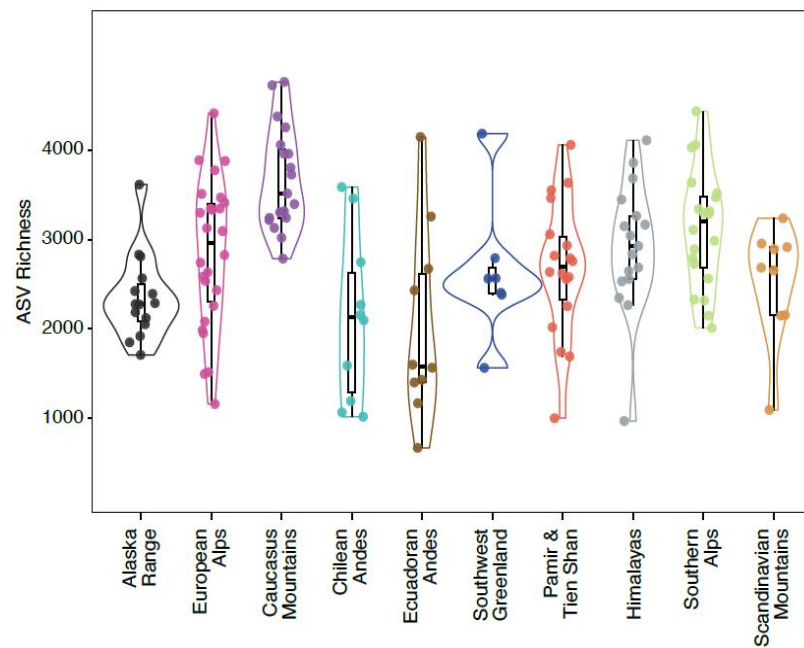
<https://doi.org/10.1038/s41586-019-0000-0>

Received: 00 Month 20XX

Accepted: 00 Month 20XX

Published online: 00 Month 20XX

Leïla Ezzat<sup>1,2\*</sup>, Hannes Peter<sup>3</sup>, Massimo Bourquin<sup>1</sup>, Susheel Bhanu Busi<sup>3,4</sup>, Grégoire Michoud<sup>1</sup>, Stilianos Fodelianakis<sup>1</sup>, Tyler J. Kohler<sup>1,5</sup>, Thomas Lamy<sup>2</sup>, Aileen Geers<sup>1</sup>, Paraskevi Pramateftaki<sup>1</sup>, Florian Baier<sup>1</sup>, Ramona Marasco<sup>6</sup>, Daniele Daffonchio<sup>6</sup>, Nicola Deluigi<sup>1</sup>, Paul Wilmes<sup>4</sup>, Michail Styllas<sup>1,7</sup>, Martina Schön<sup>1</sup>, Matteo Tolosano<sup>1</sup>, Vincent De Staercke<sup>1</sup>, and Tom J. Battin<sup>1</sup>








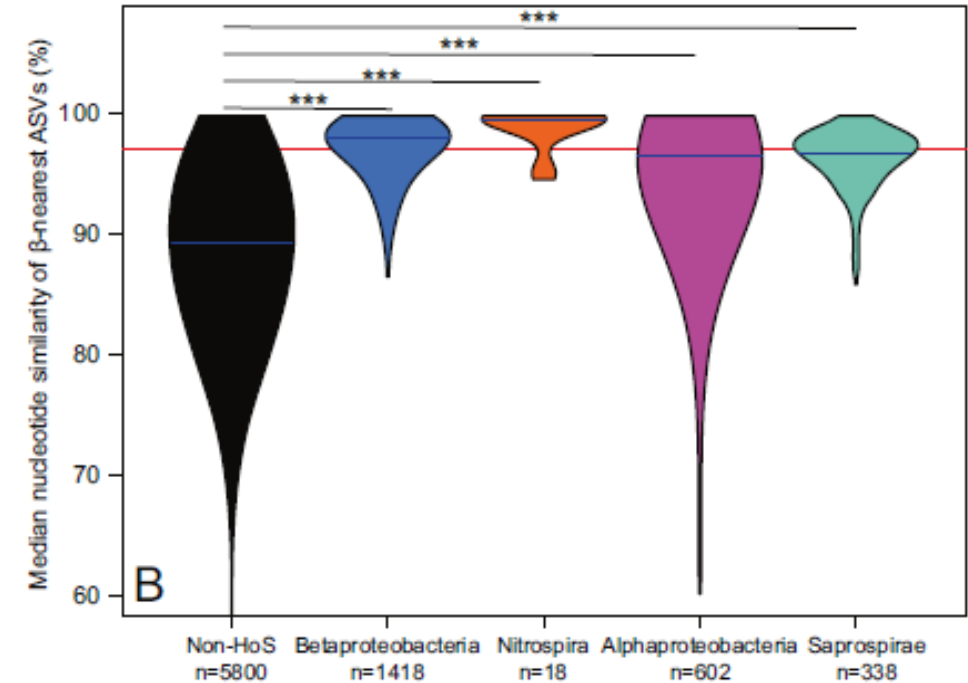
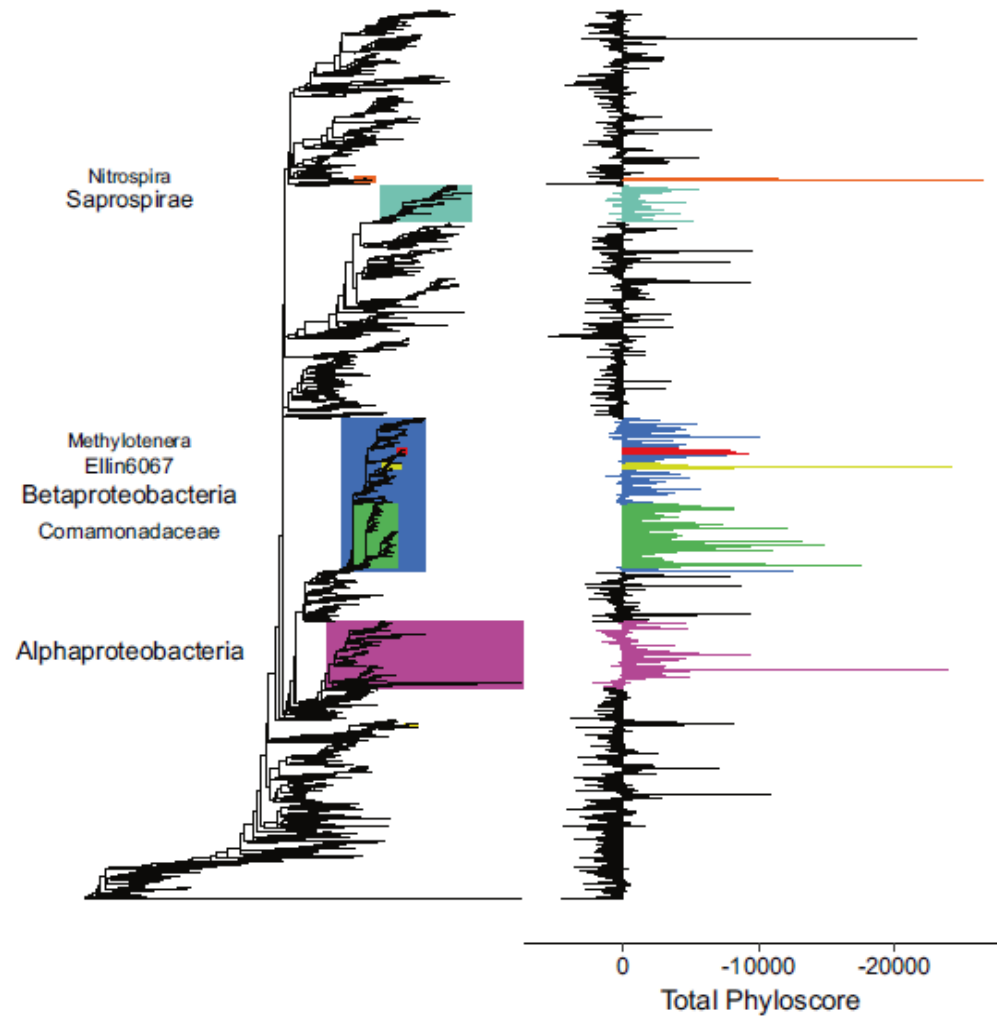
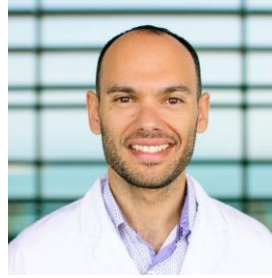
Despite the harsh conditions GFS microbial communities are highly diverse.

Across the world, GFS microbiomes are structured by spatial distance, regionality and environmental selection.

The selective environment (e.g. low nutrient availability=oligotrophy, cold temperature, unstable streambed) is similar in GFS around the world.

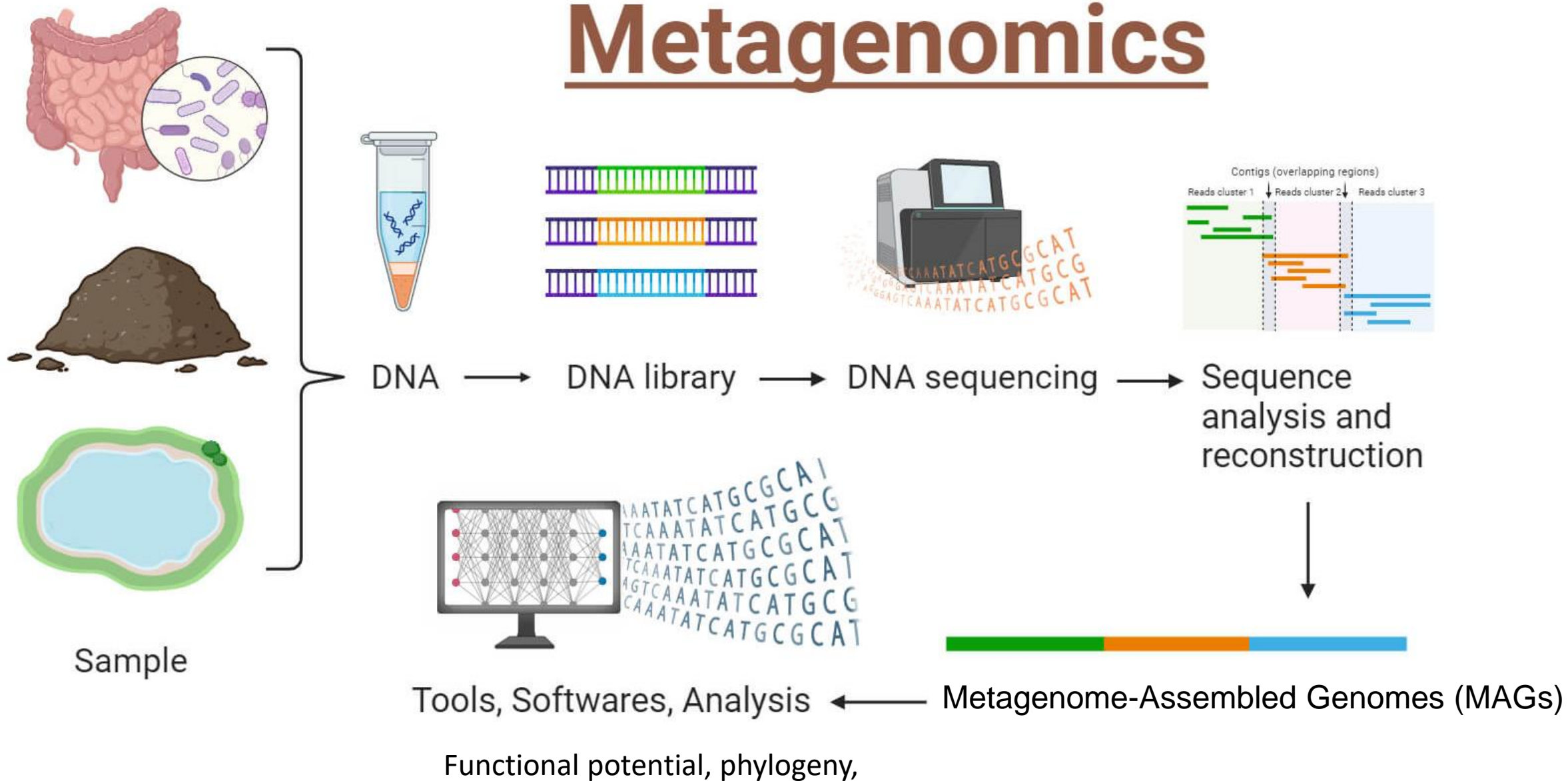
# Microdiversity characterizes prevalent phylogenetic clades in the glacier-fed stream microbiome

Stilianos Fodelianakis<sup>1</sup> , Alex D. Washburne<sup>2</sup>, Massimo Bourquin<sup>1</sup> , Paraskevi Pramateftaki<sup>1</sup>, Tyler J. Kohler<sup>1</sup>, Michail Styllas<sup>1</sup> , Matteo Tolosano<sup>1</sup>, Vincent De Staercke<sup>1</sup>, Martina Schön<sup>1</sup>, Susheel Bhanu Busi<sup>3</sup>, Jade Brandani<sup>1</sup>, Paul Wilmes<sup>3</sup> , Hannes Peter<sup>1</sup> and Tom J. Battin<sup>1</sup> 



Extreme environmental conditions select for phylogenetically related clades. These clades can regionally diversify and become microdiverse.

# Metagenomics

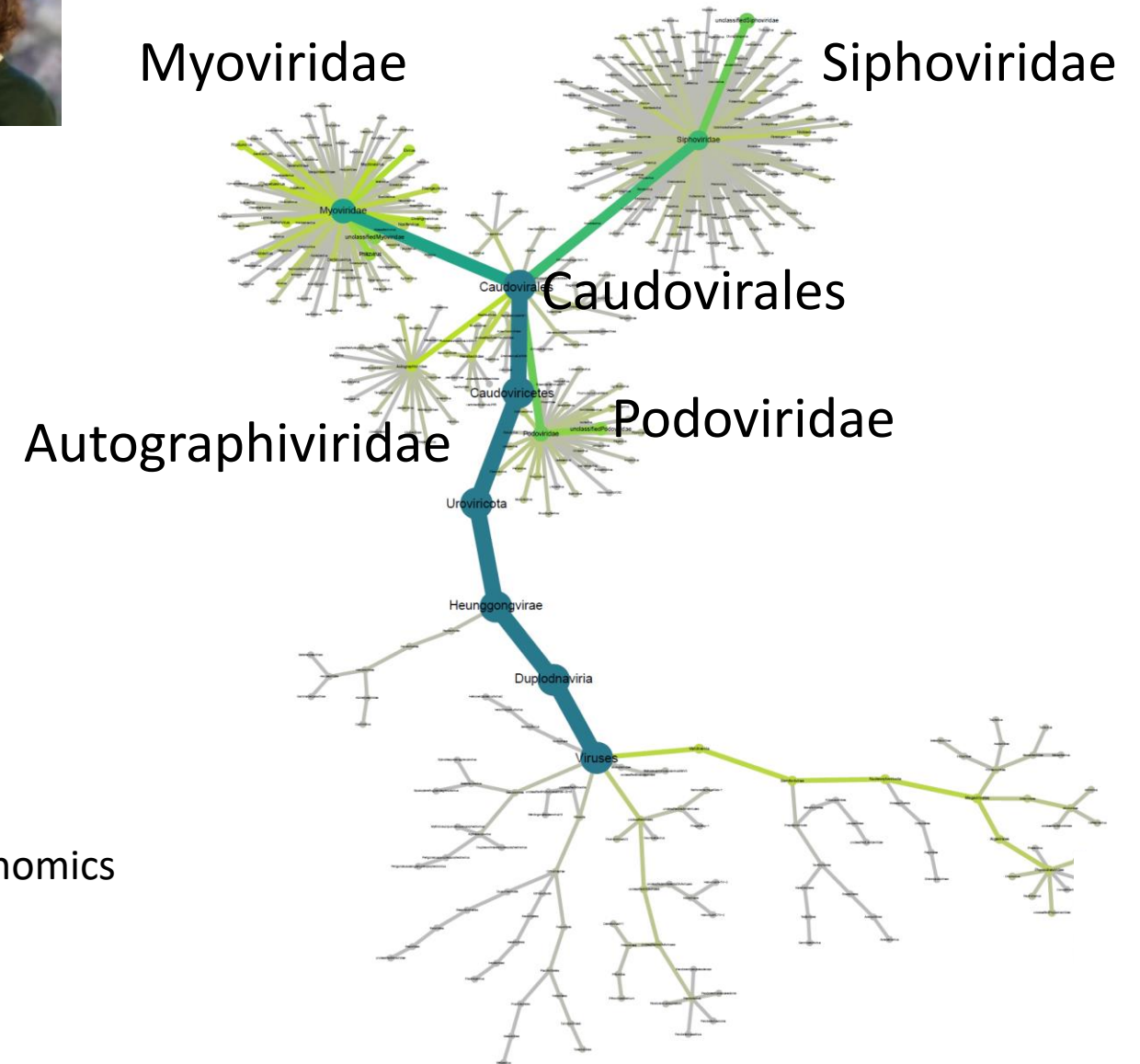
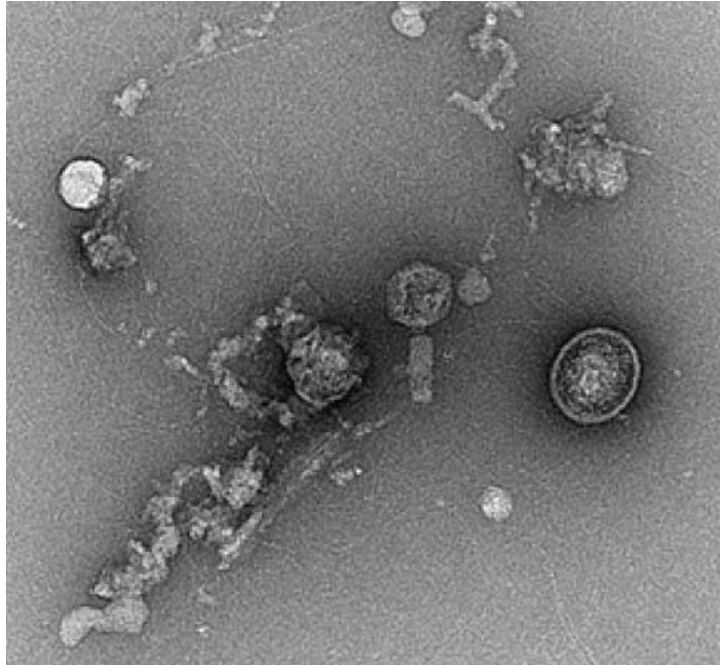




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Check for updates

# Viral diversity is linked to bacterial community composition in alpine stream biofilms

Meriem Bekliz<sup>1</sup>, Paraskevi Pramateftaki<sup>1</sup>, Tom Jan Battin<sup>1</sup> and Hannes Peter<sup>1</sup>

Studies on viruses in stream biofilms are scarce – metagenomics (viromics) allows first insights into their diversity.

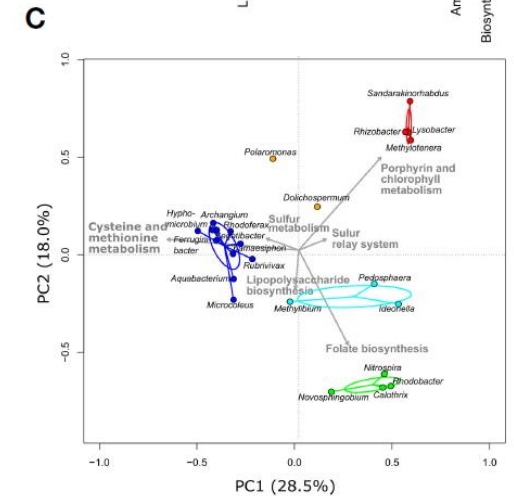
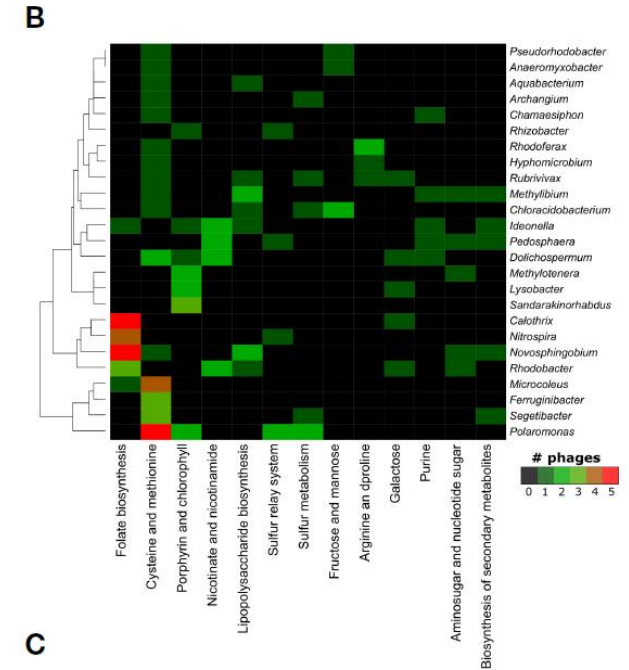
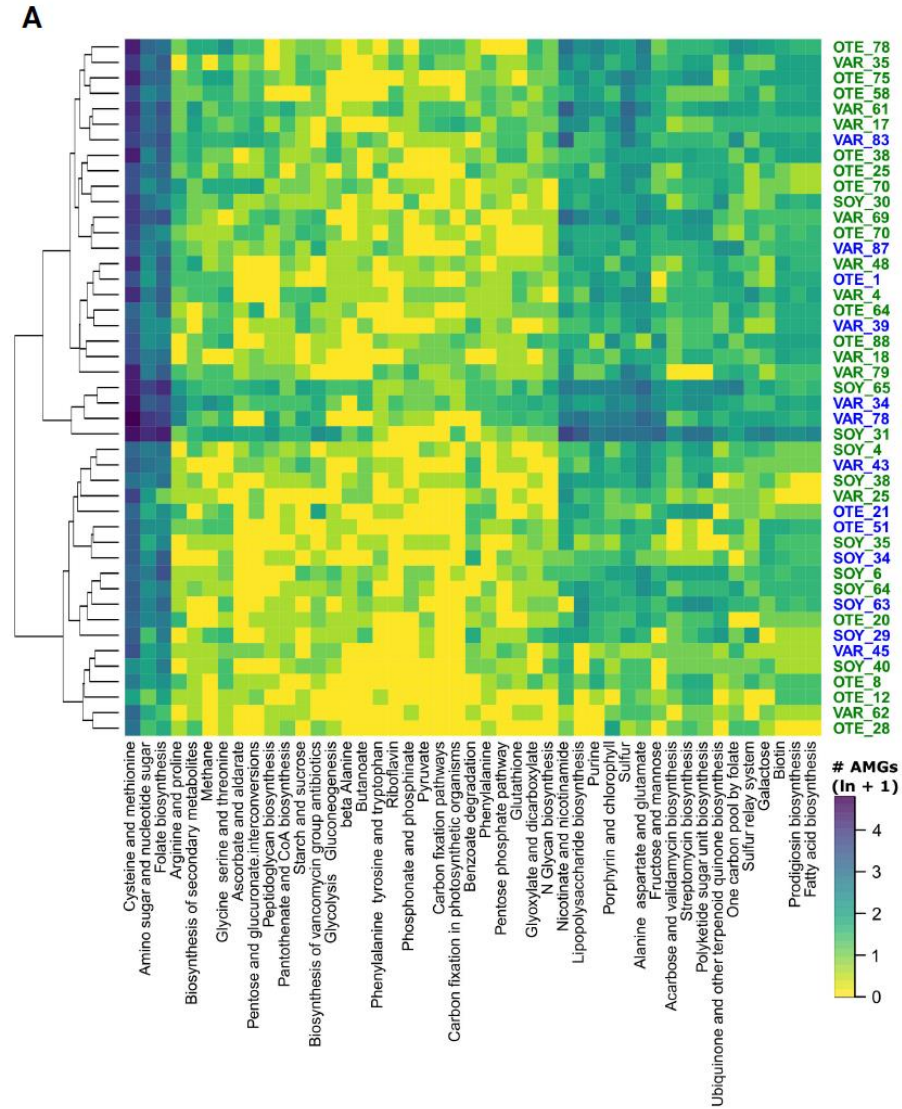
Stream biofilm viral communities are highly diverse.

Viral and bacterial community composition is coupled (correlated).

# The role of phages for microdiverse bacterial communities in proglacial stream biofilms

Hannes Peter<sup>1\*</sup>, Grégoire Michoud<sup>1</sup>, Susheel Bhanu Busi<sup>2,3</sup> and Tom J. Battin<sup>1</sup>

Viruses specific to bacteria living in glacier-fed streams carry beneficial genes (auxiliary metabolic genes)



# Climate-change experiments

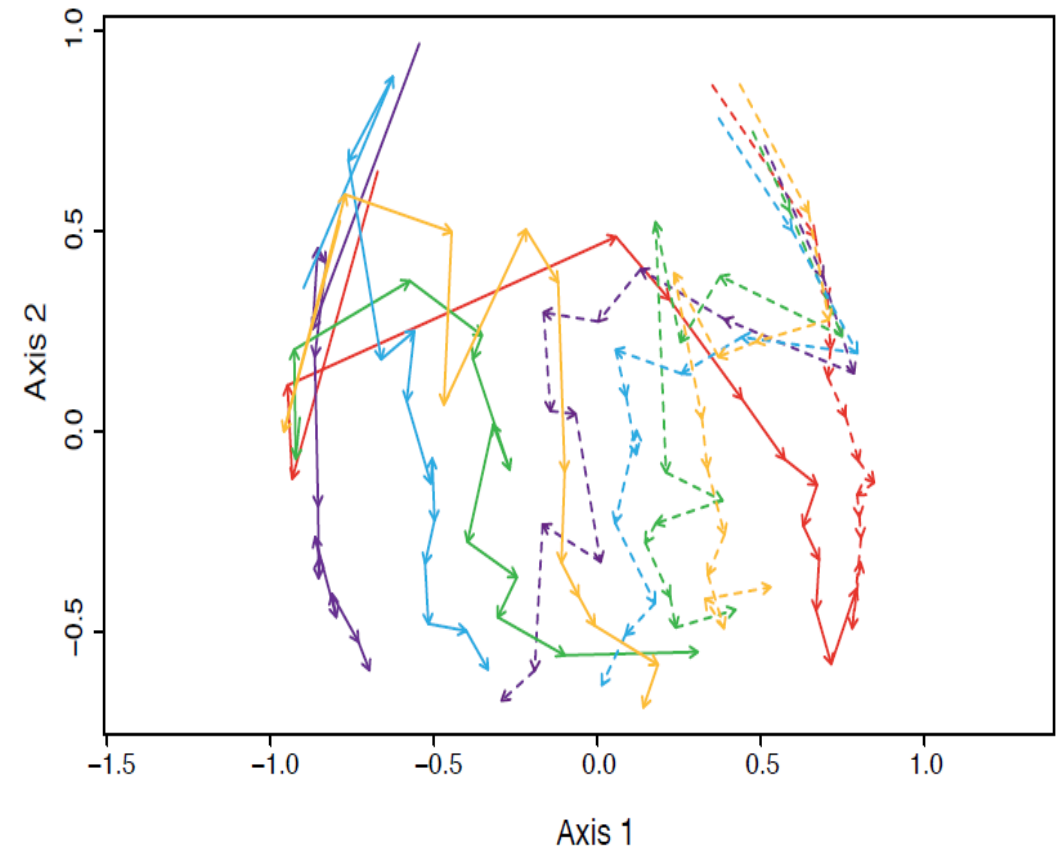
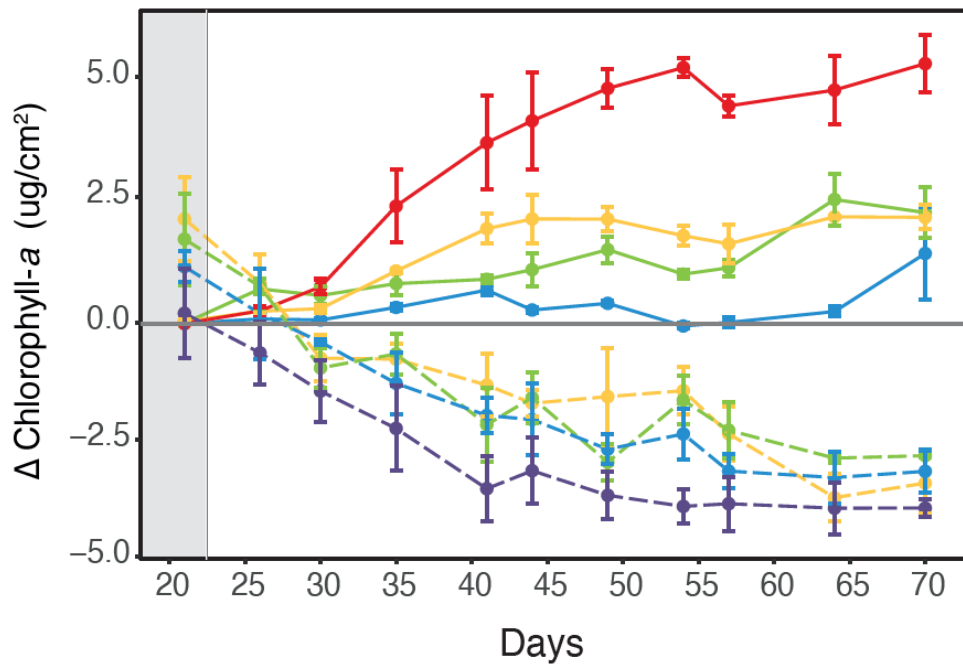
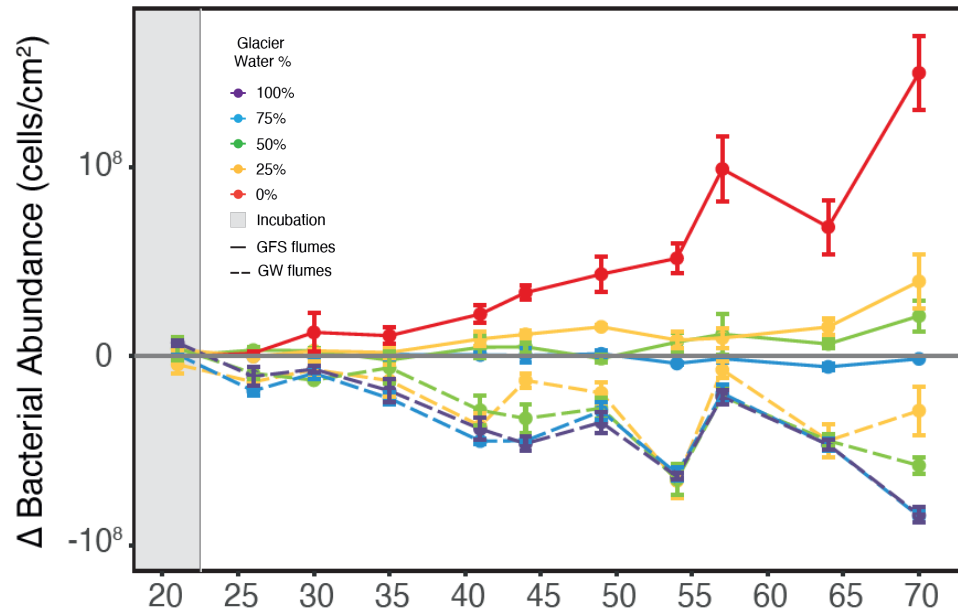


Block 1 (15 flumes)

Block 2 (15 flumes)



Microbial communities act as sentinels of climate change.



Microbial communities respond very sensitively to simulated climate change.

# TAKE HOME PART 2

- **Most microbes prefer a sessile (attached) lifestyle - embedded in complex biofilm communities**
- **River biofilms are highly diverse, the microbes in these communities drive important ecosystem functions**
- **The flow of water, the diffusion of oxygen and nutrients shape biofilm morphology**
- **Molecular tools provide insights into the diversity, distribution and function of complex microbial communities**
- **Despite the harsh environmental conditions, GFS harbor a high degree of microbial diversity**
- **Viruses are understudied in stream biofilms but may be important**
- **Global-change experiments allow mechanistic insights into the responses of microbial assemblages to change**

A wide-angle photograph of a mountain valley. In the foreground, a river flows through a rocky, sparsely vegetated landscape. The middle ground shows a valley floor with a mix of rocks and patches of green grass. In the background, steep, rocky mountains rise, some with patches of snow and glaciers. The sky is blue with scattered white clouds.

**Thank you for your attention!  
Questions?!**