

Reporting Summary

Nature Portfolio wishes to improve the reproducibility of the work that we publish. This form provides structure for consistency and transparency in reporting. For further information on Nature Portfolio policies, see our [Editorial Policies](#) and the [Editorial Policy Checklist](#).

Statistics

For all statistical analyses, confirm that the following items are present in the figure legend, table legend, main text, or Methods section.

n/a	Confirmed
☐	☒ The exact sample size (<i>n</i>) for each experimental group/condition, given as a discrete number and unit of measurement
☐	☒ A statement on whether measurements were taken from distinct samples or whether the same sample was measured repeatedly
☐	☒ The statistical test(s) used AND whether they are one- or two-sided <i>Only common tests should be described solely by name; describe more complex techniques in the Methods section.</i>
☐	☒ A description of all covariates tested
☐	☒ A description of any assumptions or corrections, such as tests of normality and adjustment for multiple comparisons
☐	☒ A full description of the statistical parameters including central tendency (e.g. means) or other basic estimates (e.g. regression coefficient) AND variation (e.g. standard deviation) or associated estimates of uncertainty (e.g. confidence intervals)
☐	☒ For null hypothesis testing, the test statistic (e.g. <i>F</i> , <i>t</i> , <i>r</i>) with confidence intervals, effect sizes, degrees of freedom and <i>P</i> value noted <i>Give P values as exact values whenever suitable.</i>
☒	☐ For Bayesian analysis, information on the choice of priors and Markov chain Monte Carlo settings
☒	☐ For hierarchical and complex designs, identification of the appropriate level for tests and full reporting of outcomes
☒	☐ Estimates of effect sizes (e.g. Cohen's <i>d</i> , Pearson's <i>r</i>), indicating how they were calculated

Our web collection on [statistics for biologists](#) contains articles on many of the points above.

Software and code

Policy information about [availability of computer code](#)

Data collection	N.A.
Data analysis	All data were analyses using R (version 4.4.1). All codes are available on github.com/laylaeb/GFS_biogeo2023

For manuscripts utilizing custom algorithms or software that are central to the research but not yet described in published literature, software must be made available to editors and reviewers. We strongly encourage code deposition in a community repository (e.g. GitHub). See the Nature Portfolio [guidelines for submitting code & software](#) for further information.

Data

Policy information about [availability of data](#)

All manuscripts must include a [data availability statement](#). This statement should provide the following information, where applicable:

- Accession codes, unique identifiers, or web links for publicly available datasets
- A description of any restrictions on data availability
- For clinical datasets or third party data, please ensure that the statement adheres to our [policy](#)

Raw sequence data have been deposited in the Sequence Read Archives with NCBI BioProject accession no. PRJNA781406. Processed data along with data tables associated with main and extended figures can be retrieved from Zenodo at doi:10.5281/zenodo.13897903. Data retrieval URL: <https://zenodo.org/records/13897903>.

Human research participants

Policy information about [studies involving human research participants and Sex and Gender in Research](#).

Reporting on sex and gender

Population characteristics

Recruitment

Ethics oversight

Note that full information on the approval of the study protocol must also be provided in the manuscript.

Field-specific reporting

Please select the one below that is the best fit for your research. If you are not sure, read the appropriate sections before making your selection.

☐ Life sciences ☐ Behavioural & social sciences ☒ Ecological, evolutionary & environmental sciences

For a reference copy of the document with all sections, see nature.com/documents/nr-reporting-summary-flat.pdf

Ecological, evolutionary & environmental sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	Field work at ca 150 glacier-fed streams around the world strictly following established standard operational procedures and trained personnel. Study systems were selected to cover the major mountain ranges, comply with geopolitical conditions, Covid-19 related context and field safety, covering altitudes from 2000 to 4800 m above sea level.
Research sample	We sampled the benthic sandy sediments of glacier fed streams as this fraction contributes most surface area for microbial colonisation per unit streambed surface area. DNA was extracted from these sediments. We also collected water samples for physico-chemical characterisation. We inferred glaciological metrics from satellite imagery and GIS. Sediments were also analysed for mineral composition.
Sampling strategy	As aforementioned, we covered the major glacierized mountain ranges across the continents. Per mountain range, we selected up to three regions to have representative sample at the scale of the mountain range. Per region, we identified up to 4 glacier-fed streams with different glacier size etc. Per stream, we sampled three sediment patches in a reach as close to the glacier snout as possible (depending on safety and accessibility). All samples for microbiological analyses flash-frozen (liquid nitrogen) immediately upon collection in the field. Temperature chain always (!! kept until handling in the lab at EPFL, Switzerland.
Data collection	The PI's (Battin) lab collected all samples to ensure the highest level of reproducibility and comparability possible. All DNA was extracted and libraries constructed in the PI's lab by the same two well-trained technicians (again to reduce bias etc). Sequencing was done at KAUST, data analyses at EPFL (Scitas computer) and University of Luxembourg (HPC).
Timing and spatial scale	Expeditions (up to 2.5 months each) were conducted over four entire years, also during the Covid-19 pandemics. The design was such that we sampled glacier-fed streams once either during the vernal or autumnal 'window of opportunity' when environmental conditions were less extreme. For this, we basically traveled with the seasons depending on the hemisphere. This is critical allow comparability across systems.
Data exclusions	A small percentage of samples was excluded because not enough DNA was extracted, which simply reduced the overall number of cases. Few ASVs excluded because they were identified in mock communities
Reproducibility	This is a large-scale spatial survey of complex systems. Hence it is clear that reproducibility at the level of streams is simply not feasible. However (!), we did reproduce at the level of sediment patches (triplicates) sampled per stream reach.
Randomization	none
Blinding	Mock communities (DNA, Zymo, Cat Nr. 6305 and cell cultures Culture, Zymo Cat Nr. 6300) as well as sequencing blanks were used.

Did the study involve field work? ☒ Yes ☐ No

Field work, collection and transport

Field conditions	Challenging field conditions, well met by highly trained personnel. Safety regulations, regular medical checks and access respected.
Location	Detailed map shown in Extended Data Fig 1 with the Southern Alps of New Zealand, Himalayas, Caucasus Mountains, Pamir and Tian Shan, European Alps, Scandinavian Mountains, Southwest Greenland, Alaska Range, African Rwenzori and both Ecuadorian and Chilean Andes
Access & import/export	We had all required permits for sampling and sample exports. New Zealand: Ministry of Conservation (#72437 – RES); Greenland: Ministry of Industry and Energy (# G19-016); Russia: Ministry of Natural Resources and Environment (Permit granted to IGRAS base on the signed MoU); Ecuador: Ministerio del Ambiente, Direccion Nacional de Biodiversidad; we worked under the global research permit of Escuela Politécnica Nacional); Norway: Norwegian Environment Agency; France (Permissions authorized through the collaboration between EPFL – RIVER Lab and academic and governmental and non-governmental entities in France); Nepal (Research permit from Department of National Parks and Wildlife Conservation; Trekking permits (TIMS) for Sagamatha, Langtang National Parks & Annapurna Conservation Area); Kyrgyzstan (Government of Kyrgyz Republic, Ministry of Environment; Border Zone Permits and Research permits obtained under MoU with CAIAG); Uganda (Uganda National Council for Science and Technology UNCST, # NS291ES, Uganda Wildlife Authority UWA, # COD/96/05); Chile (Ministère de l'Agriculture, La Corporación Nacional Forestal, CONAF # 9.494.705-7); Alaska (US Forest Service USFS Authorization permit GLA1207 FS, Department of Natural Resources DNR Division of Parks & Outdoor Recreation Special Park Use Permit 11 AAC 18.010)
Disturbance	none

Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

Materials & experimental systems

n/a	Involved in the study
☒	☐ Antibodies
☒	☐ Eukaryotic cell lines
☒	☐ Palaeontology and archaeology
☐	☒ Animals and other organisms
☒	☐ Clinical data
☒	☐ Dual use research of concern

Methods

n/a	Involved in the study
☒	☐ ChIP-seq
☒	☐ Flow cytometry
☒	☐ MRI-based neuroimaging

Animals and other research organisms

Policy information about [studies involving animals](#); [ARRIVE guidelines](#) recommended for reporting animal research, and [Sex and Gender in Research](#)

Laboratory animals	not applicable
Wild animals	Benthic biofilm microorganisms
Reporting on sex	not applicable
Field-collected samples	As described above, all sediment sampled for microbiological analyses were deep-frozen at the spot in liquid nitrogen (dewars carried up to 5,200 m a.s.l.), the temperature chain unbroken until handling in the lab. Liquid samples frozen or stored cool in the dark - prefiltered in precombusted vials. Sediments sampled with flame sterilized stainless equipment.
Ethics oversight	None required. However, we had permissions from the various authorities to enter national reserves or Maori territory in NZ, for instance.

Note that full information on the approval of the study protocol must also be provided in the manuscript.