BiodivRestore Project „Restolink“

Final project meeting and expert workshop Oct 13th – Oct 17th 2025

Summary final meeting

On 13 October 2025, the Restolink consortium convened in Leipzig for the first day of the final project meeting, with the overarching aim of synthesizing results across all work packages to evaluate the effects of river restoration in relation to key environmental covariates and to align remaining analyses and dissemination strategies toward project completion. Day 1 was dedicated to synthesis-oriented evaluation across work packages, following the overarching goal that each WP should deliver a statistically grounded assessment of restoration effects and their modulation by contextual covariates such as biome. After a brief welcome and framing of the day's objectives, the meeting progressed through structured WP presentations and discussions, emphasizing integration, remaining analytical needs, and publication strategies.

Discussions in WP1 (Hydromorphology and Greenhouse Gases) focused on the transition from data generation to final analyses and interpretation. Core hydromorphological datasets are largely complete, with remaining post-processing efforts focused on roughness metrics and re-evaluation of flow data. Given uneven data availability across countries, participants agreed to prioritize detailed roughness analyses for selected stream triplets and to improve transparency by compiling a cross-scale data availability matrix. For greenhouse gas fluxes, analyses revealed high site-specific variability, with no consistent cross-country patterns. While the analytical work was completed, the group critically reflected on whether these results should be formally reported within Restolink or more strategically positioned within a potential follow-up project, particularly to enable stronger integration of longitudinal production–consumption dynamics.

The WP2 session (Macroinvertebrates and Microbiota) confirmed that biological datasets are near-complete, with only minor gaps remaining. Analyses indicate that restoration effects are contingent on biome context and restoration type, reinforcing the need for trait-based and functional interpretations. At the same time, limitations in trait data availability—especially for tropical systems—were acknowledged. For microbial communities, remaining genetic analyses are planned using existing resources, with a clear emphasis on aligning microbial functional patterns with hydromorphological and ADV-derived parameters. Across both components, strong interdependencies with WP1 outputs were highlighted as essential for mechanistic synthesis.

In WP3 (Metabolism, Organic Matter Decomposition, and Nutrient Uptake), discussions centred on harmonization and final data consolidation. Participants identified temperature correction and recovery of missing field metadata as key prerequisites for completing metabolism and decomposition analyses. Nutrient uptake measurements at the whole-stream scale are complete, while biofilm and PUC datasets are being standardized for joint re-analysis. The group agreed on coherent publication strategies that combine complementary process indicators, which enhance interpretability and synthesis potential.

The afternoon concluded with a joint session on restoration success, data management, and milestone planning (WP4–6). Progress toward a synthesis manuscript was confirmed, with responsibilities and timelines clarified and journal options discussed. Overall, the first day underscored that Restolink has entered its final integrative phase: the remaining work is highly targeted, focused on cross-WP coherence, strategic dissemination, and maximizing the project's legacy through robust synthesis rather than additional data generation.

Summary expert workshop

Building on the scientific insights generated by RESTOLINK, an expert workshop was convened from October 14th to 17th, 2025, that extended the consortium by bringing together internationally leading researchers in stream biodiversity, ecosystem functioning, and river restoration. The workshop aimed to critically reassess prevailing restoration paradigms in the context of climate change and to develop principles for climate-resilient stream and river management that move beyond purely local or historically oriented approaches. Discussions were organized in intensive breakout groups, fostering cross-disciplinary exchange and synthesis. A central outcome of the workshop is the preparation of a joint opinion paper that articulates a forward-looking roadmap for climate-adapted restoration. This framework challenges the traditional goal of restoring ecosystems to past reference states, which are increasingly unattainable under ongoing climate change. Instead, it proposes robust, climate-independent restoration objectives, identifies general measures to re-establish the fundamental elements of running-water ecosystems, and outlines an approach to prioritize site-specific actions that address stressors amplified by climate change. Importantly, the framework recognizes social acceptance as a critical prerequisite for successful implementation. By reframing restoration as a future-oriented endeavor, the workshop laid the conceptual foundation for developing resilient stream and river ecosystems under changing environmental conditions.

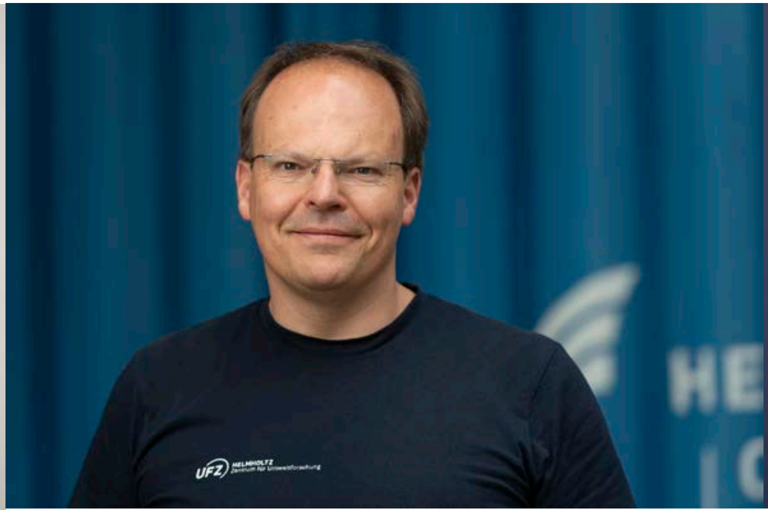
Appendix 1. Participants

Country	Name	Institution	Attendance	WP
BRA	Björn Gücker	Federal University of São João del-Rei	Presence	3
BRA	Davi Gasparini Fernandes Cunha	University of São Paulo	Online	5
ESP	Daniel von Schiller	University of Barcelona	Presence	3
ESP	Isabel Munoz	University of Barcelona	Online	2
GER	Andreas Lorke	University of Koblenz-Landau	Presence	1
GER	Clara Mendoza-Lera	University of Koblenz-Landau	Presence	1
GER	Julia Pasqualini	Helmholtz Centre for Environmental Research	Presence	2, 3
GER	Mario Brauns	Helmholtz Centre for Environmental Research	Presence	2, 3, 6
GER	Markus Weitere	Helmholtz Centre for Environmental Research	Presence	4
GER	Patrick Fink	Helmholtz Centre for Environmental Research	Presence	2
SWE	Nícolas Finkler	Umeå University	Presence	4
GER	Flavia Tromboni	Universität Kaiserslautern Landau	Presence	Expert
GER	Mathias Scholz	Helmholtz Centre for Environmental Research	Presence	Expert
GER	Mechthild Schmitt-Jansen	Helmholtz Centre for Environmental Research	Presence	Expert
NZL	Ross M. Thompson	University of Canberra	Presence	Expert
UK	Rachel Stubbington	Nottingham Trent University	Presence	Expert
USA	Amy Marcarelli	Michigan Technological University	Presence	Expert
USA	Ellen Wohl	Colorado State University	Presence	Expert
USA	G. Mathias Kondolf	University of California Berkeley	Presence	Expert
USA	Robert Hall	University of Montana	Presence	Expert
USA	Solange Filoso	University of Maryland	Presence	Expert

Supplemental Appendix. Slides of the presentations

Work package 2 – Biodiversity

by WP leads Isabel Muñoz and Patrick Fink, together with Julia Pasqualini

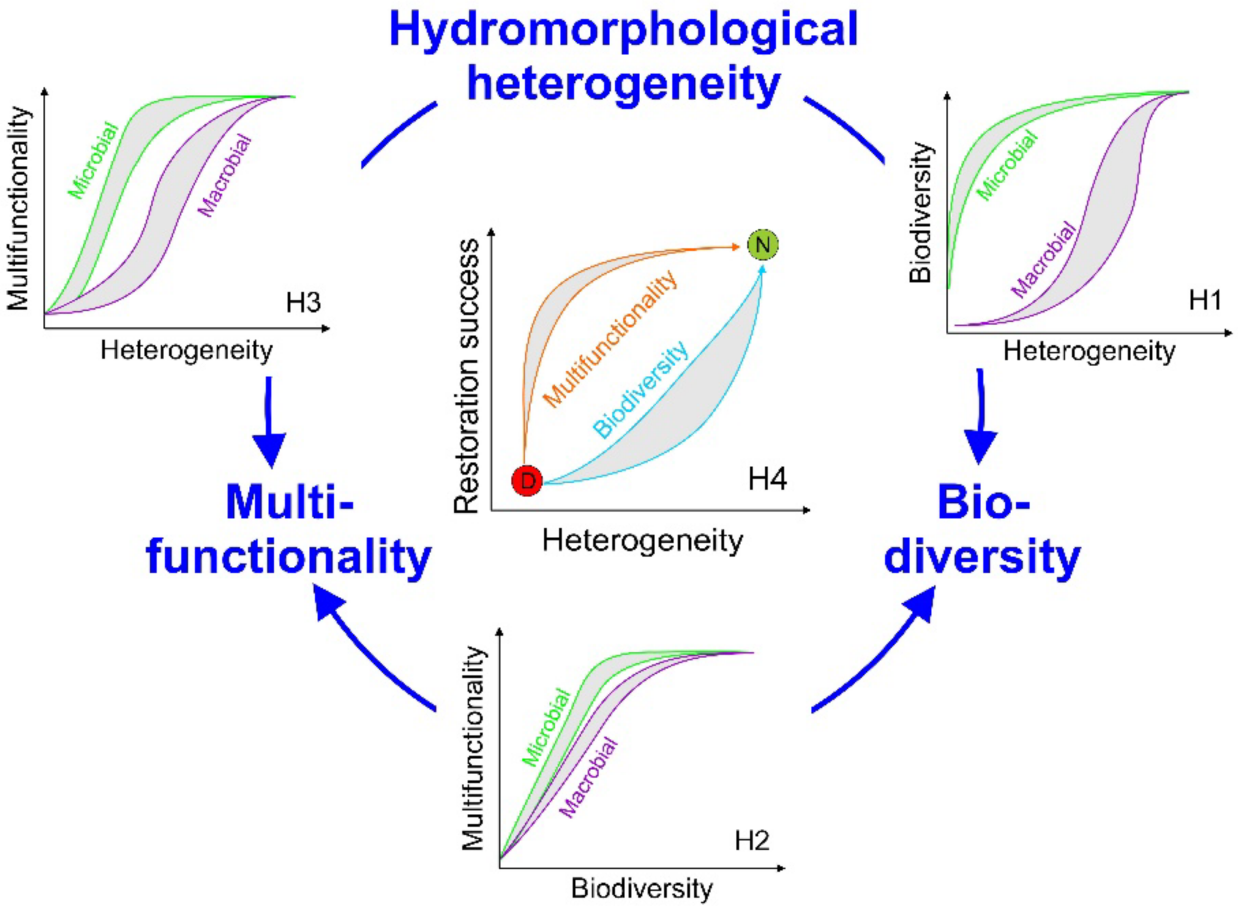




RESTOLINK synthesis workshop, Leipzig, Oct 13th, 2025

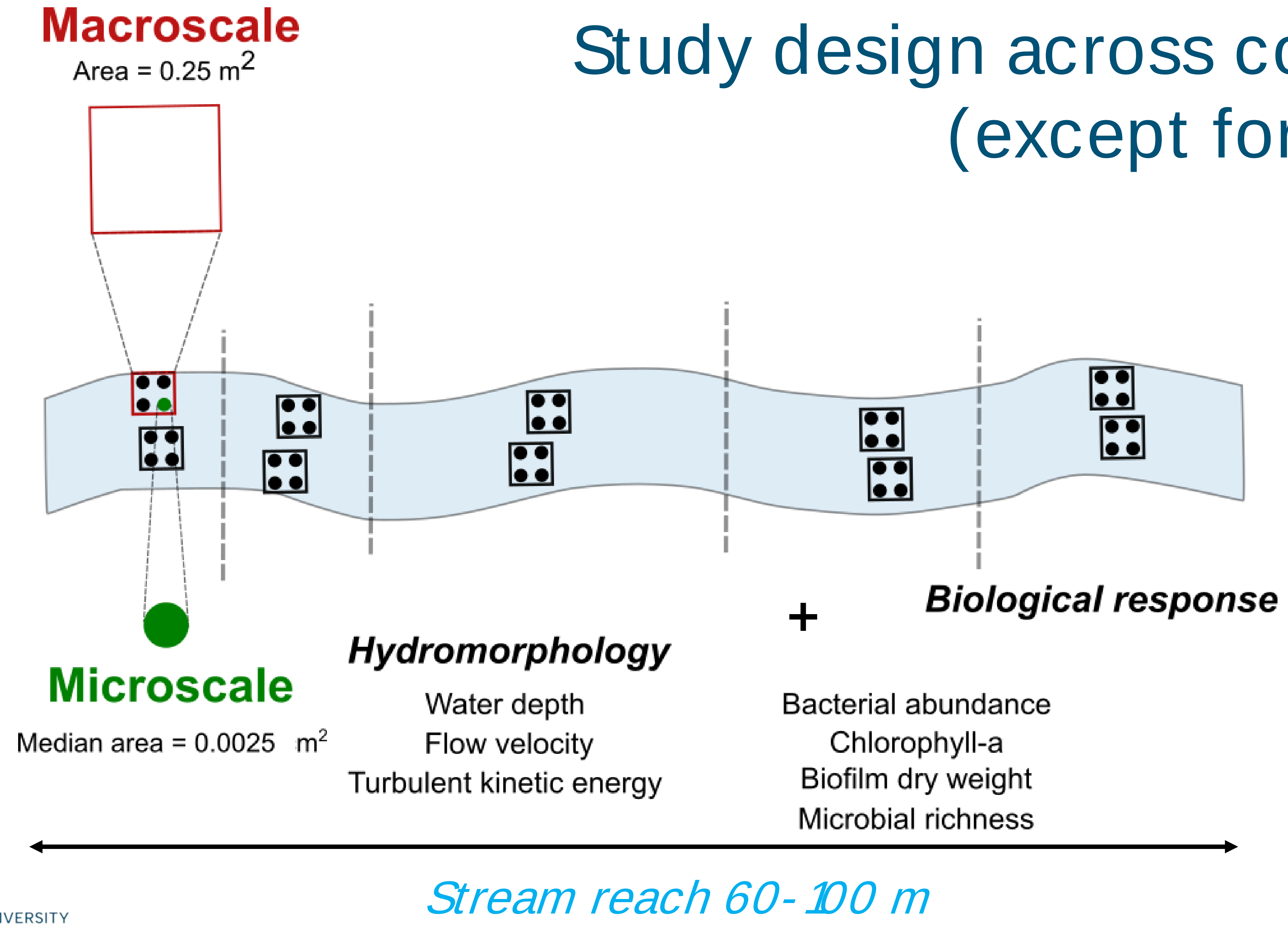
Work package 2 – Biodiversity
Initial approach and hypotheses

Hypothesis 1: Biodiversity is generally positively related to hydromorphological heterogeneity for micro- and macroorganisms in line with the habitat heterogeneity hypothesis. We expect **differences in the shape of both trajectories, given that the body size and mobility of a given species drive its niche requirements**.

Hypothesis 2: Biodiversity scales asymptotically with multifunctionality because few species contribute disproportionately to ecosystem functioning. We predict that such **functionally key species are primarily microbes** and that the inter-biome variability is primarily driven by the degree of functional redundancy.

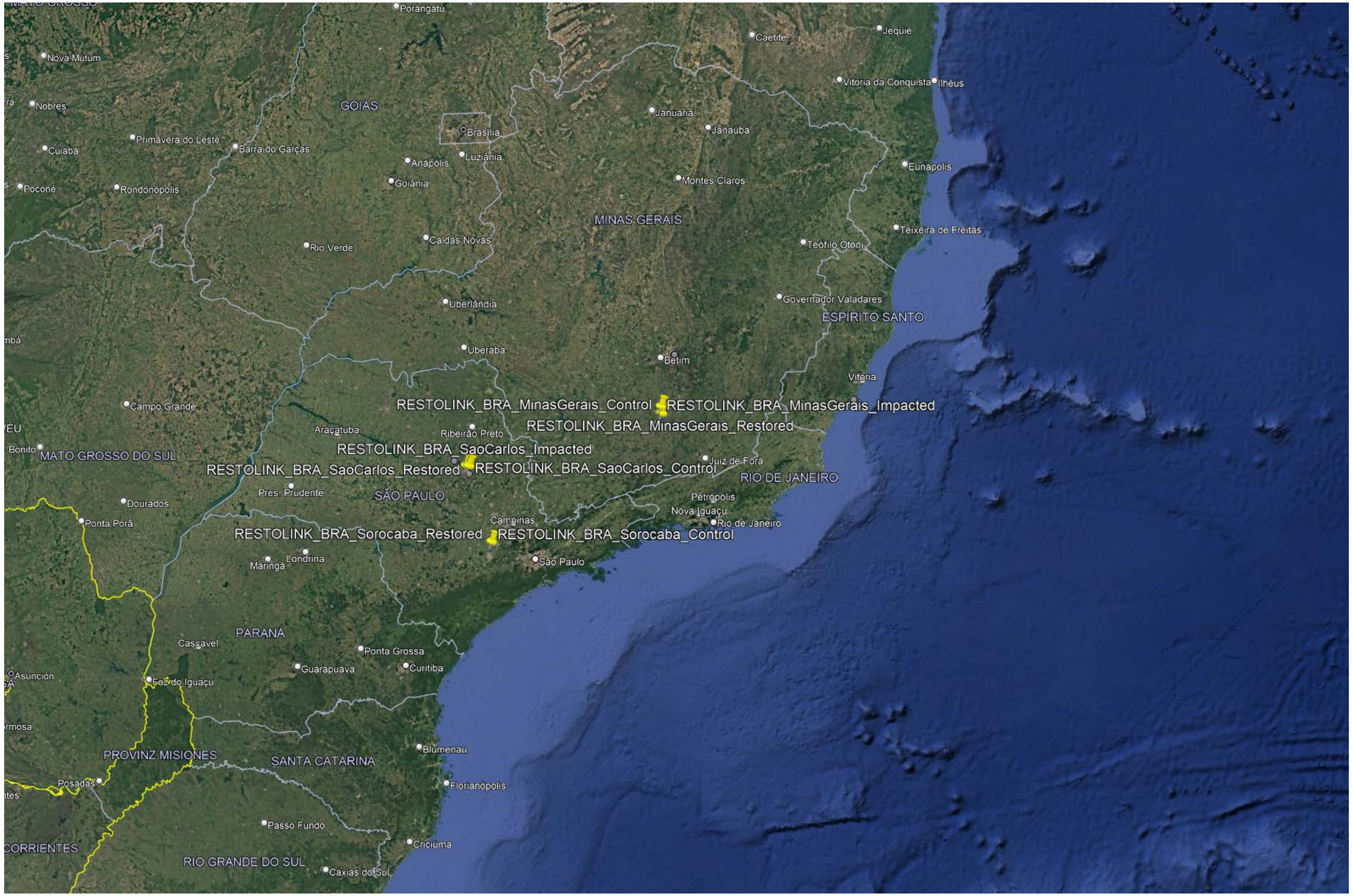


Study design across countries (except for 🇸🇪)



Study systems (BRA, ESP, GER)

Study systems (BRA )



1) Sao Carlos (Sao Paulo)
2) unnamed stream (Minas Gerais)
3) Sorocaba (Sao Paulo)

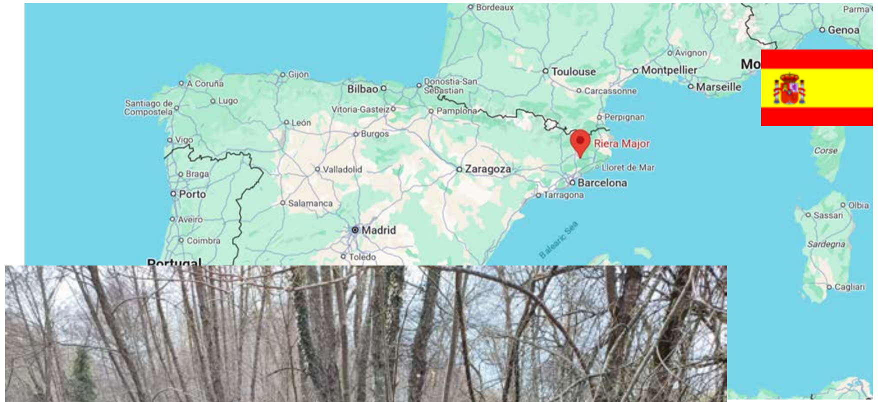
Study systems (ESP )

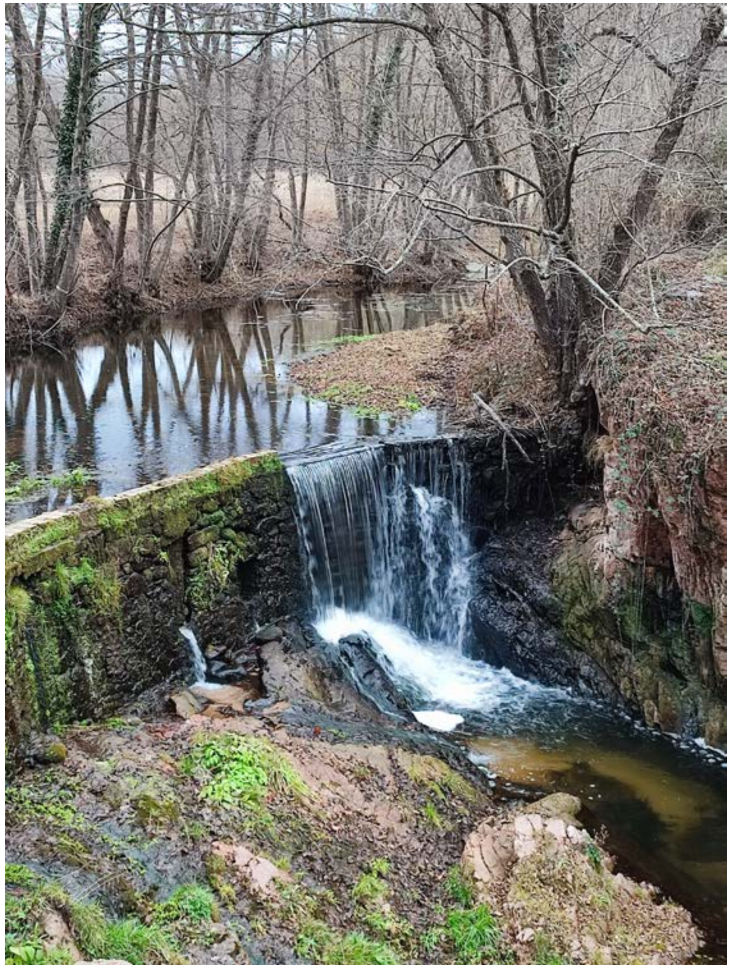
1) Riera Major (Catalunya)

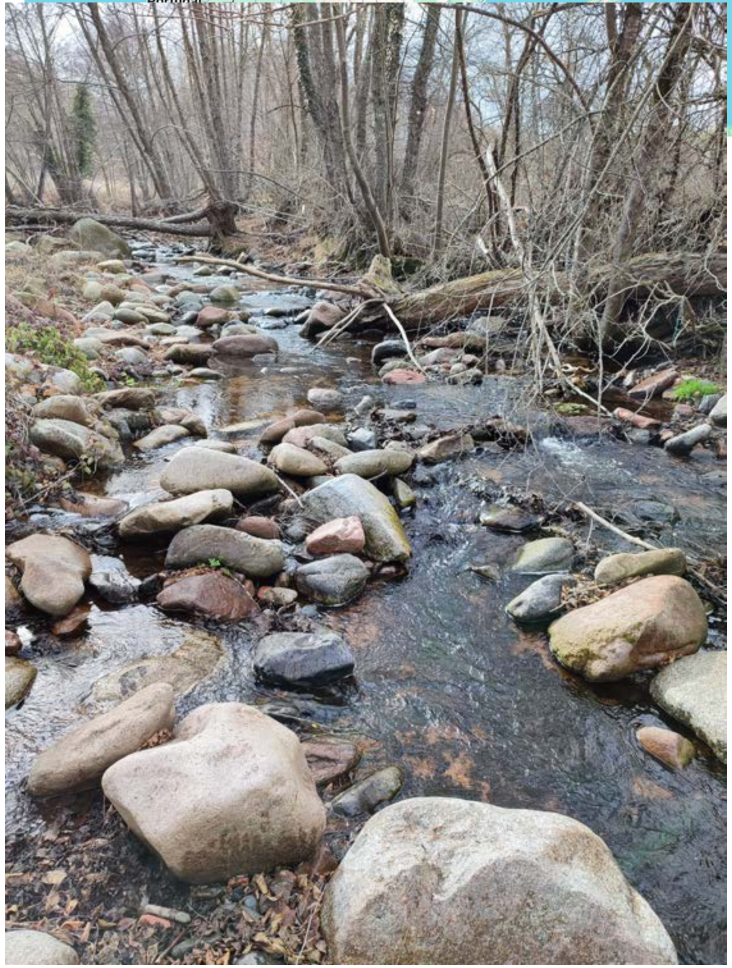
2) Ritort (Catalunya)

3) Sorreig (Catalunya)

Example triplet: Riera Major, Spain







impacted

restored

control

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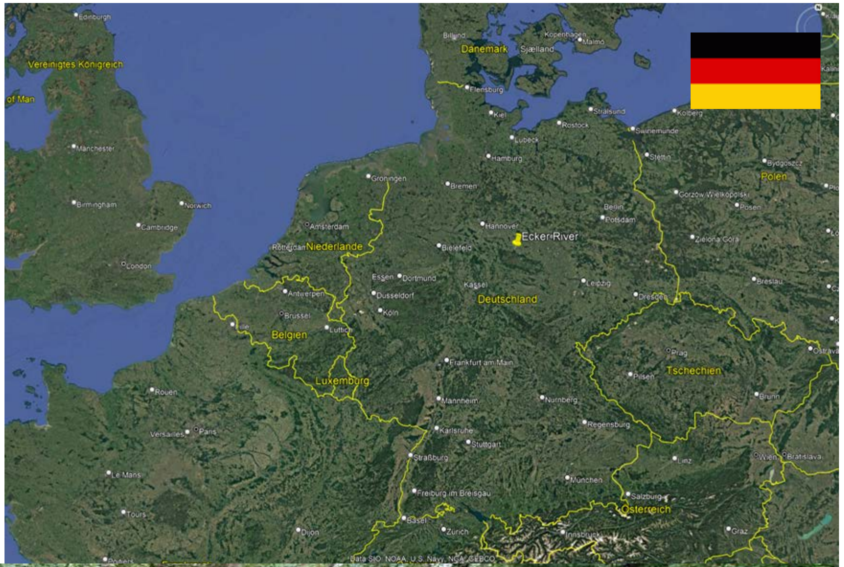
Study systems (GER )

1) Ecker
(Harz Mountains, Sachsen-Anhalt)

2) Ilse
(Harz Mountains, Sachsen-Anhalt)

3) Holtemme
(Harz Mountains, Sachsen-Anhalt)

Example triplet: Ecker, Germany



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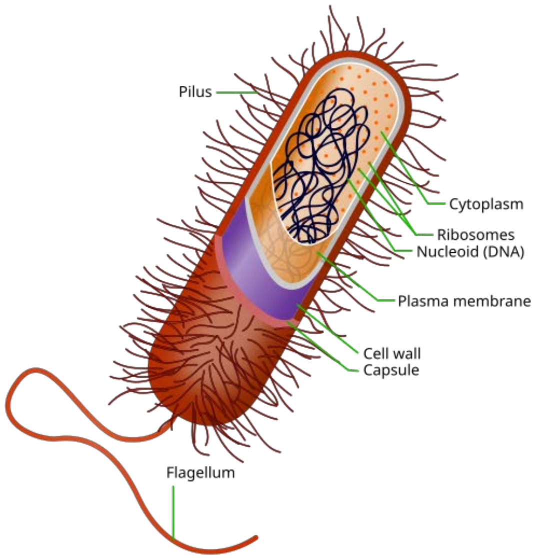
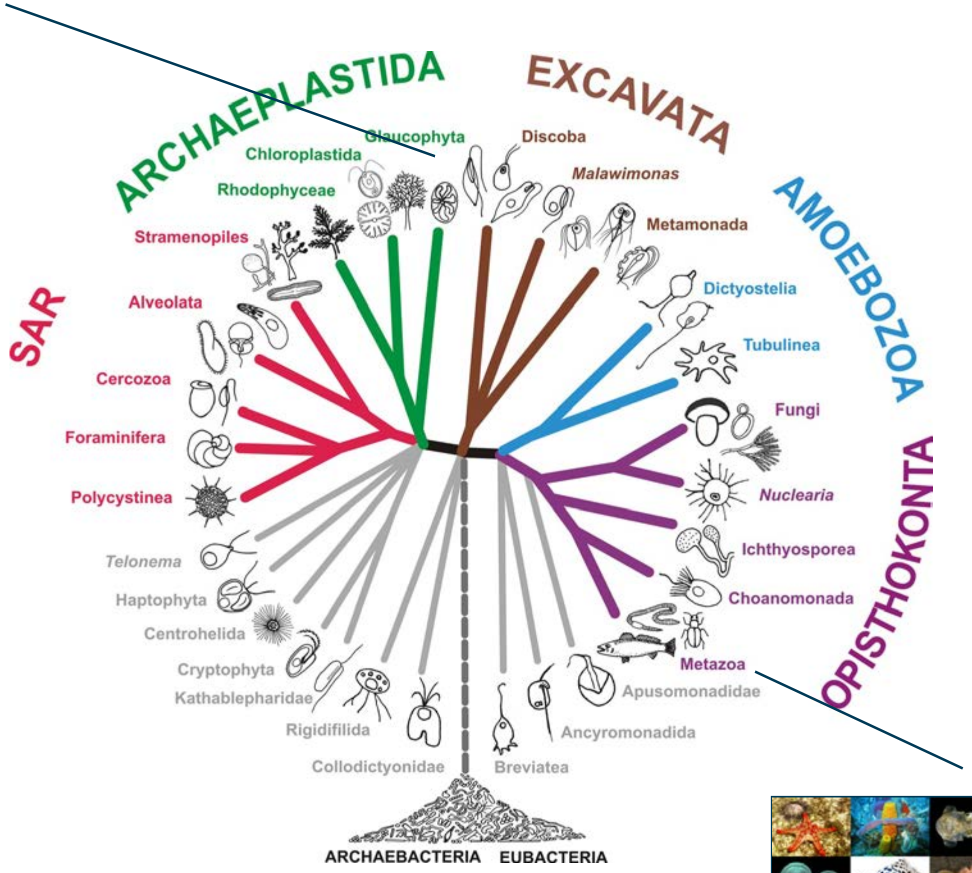
Assessing macrobial (i.e. macroinvertebrate) diversity

Surber sampling on the spot (0.25 m²) scale; subsequent counting of EtOH fixed samples

Assessing microbial diversity via DNA

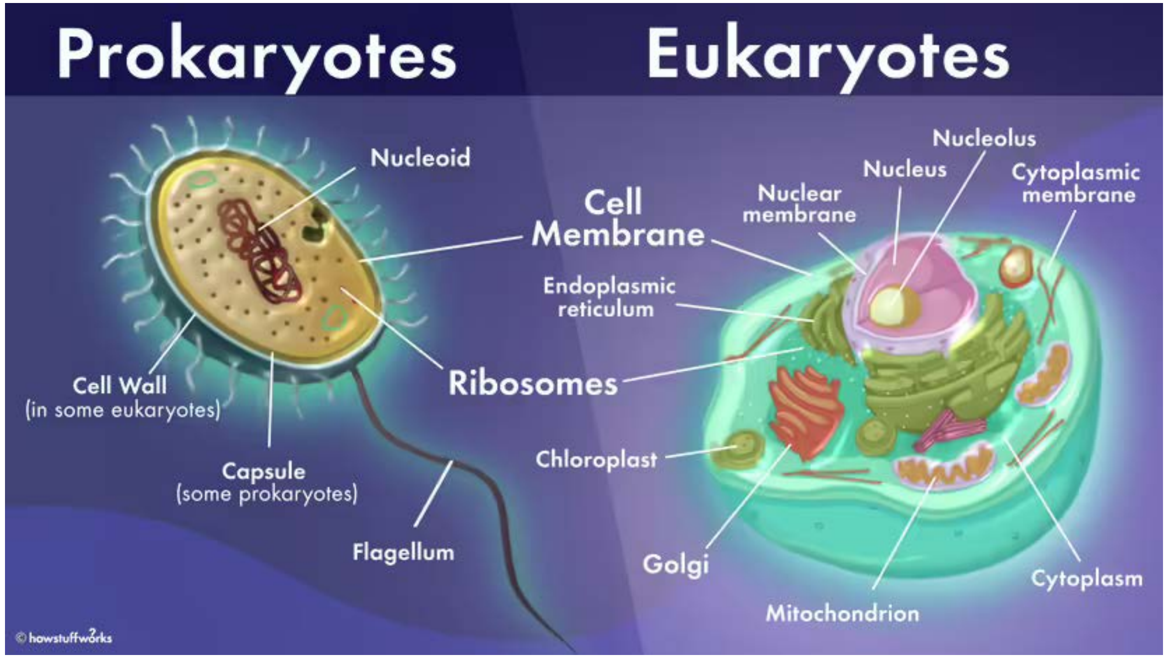


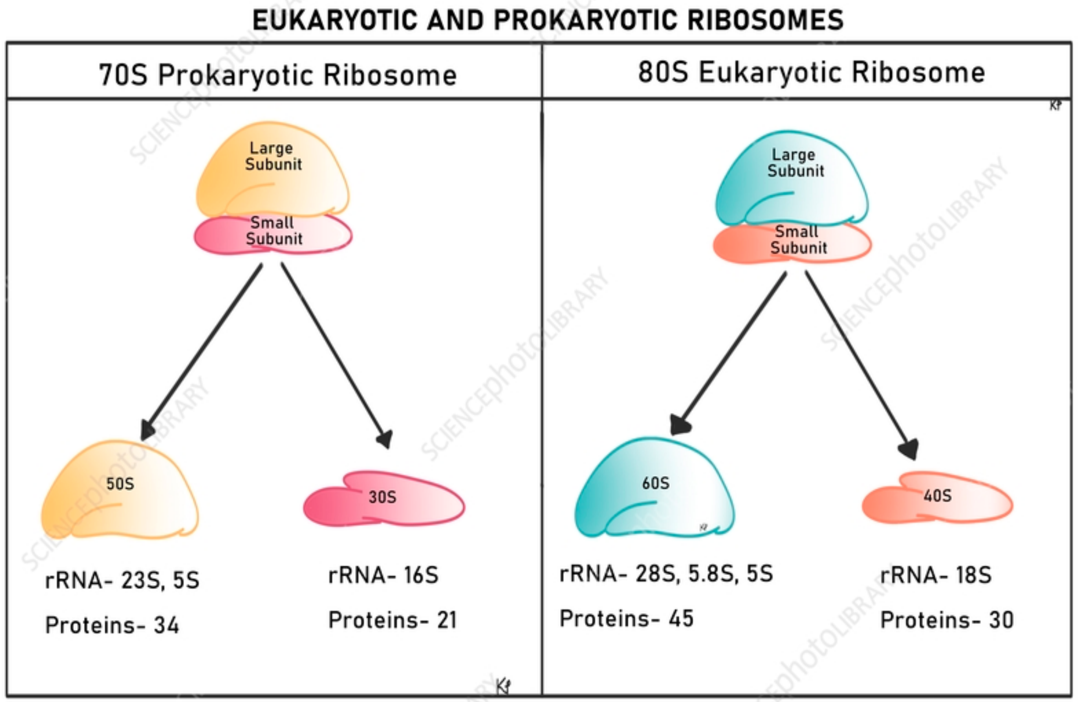
Prokaryotes (bacteria & archaea)



Eukaryotes (everything else, including algae, plants, animals, ...)

Assessing microbial diversity via DNA



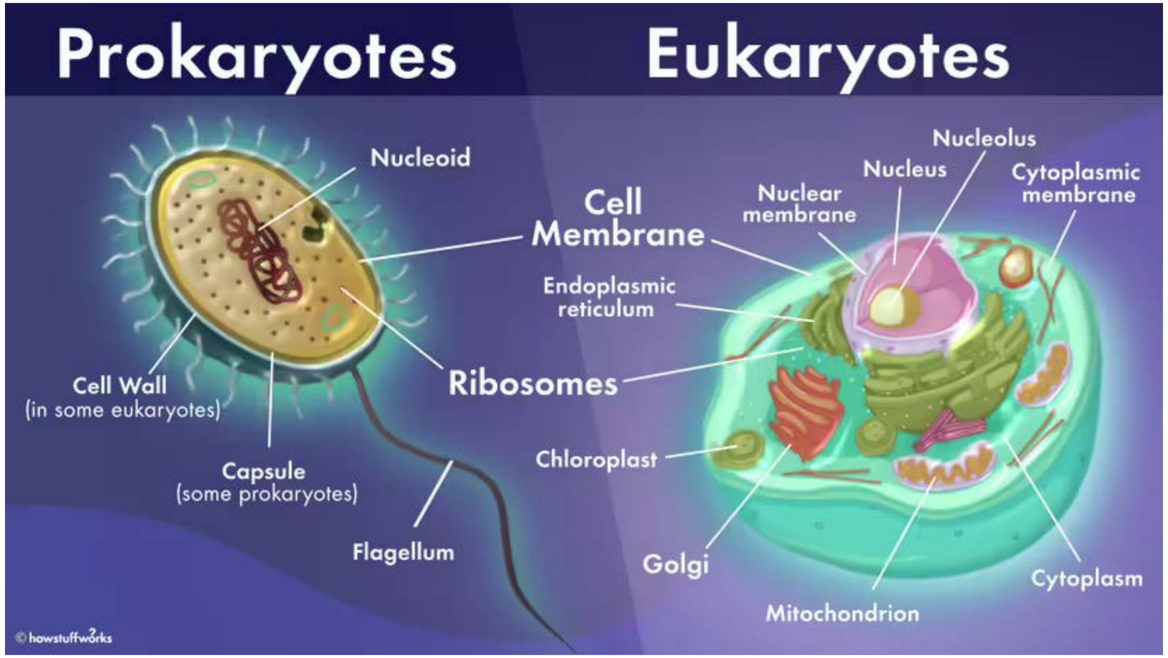


Prokaryotes (bacteria & archaea)

Prokaryotes: 16s rib. SSu 🡐 here: bacteria
Eukaryotes: 18s rib. SSu 🡐 here: ‚algae‘

Eukaryotes (everything else, including algae, plants, animals, ..)

Linking microbial diversity to functions

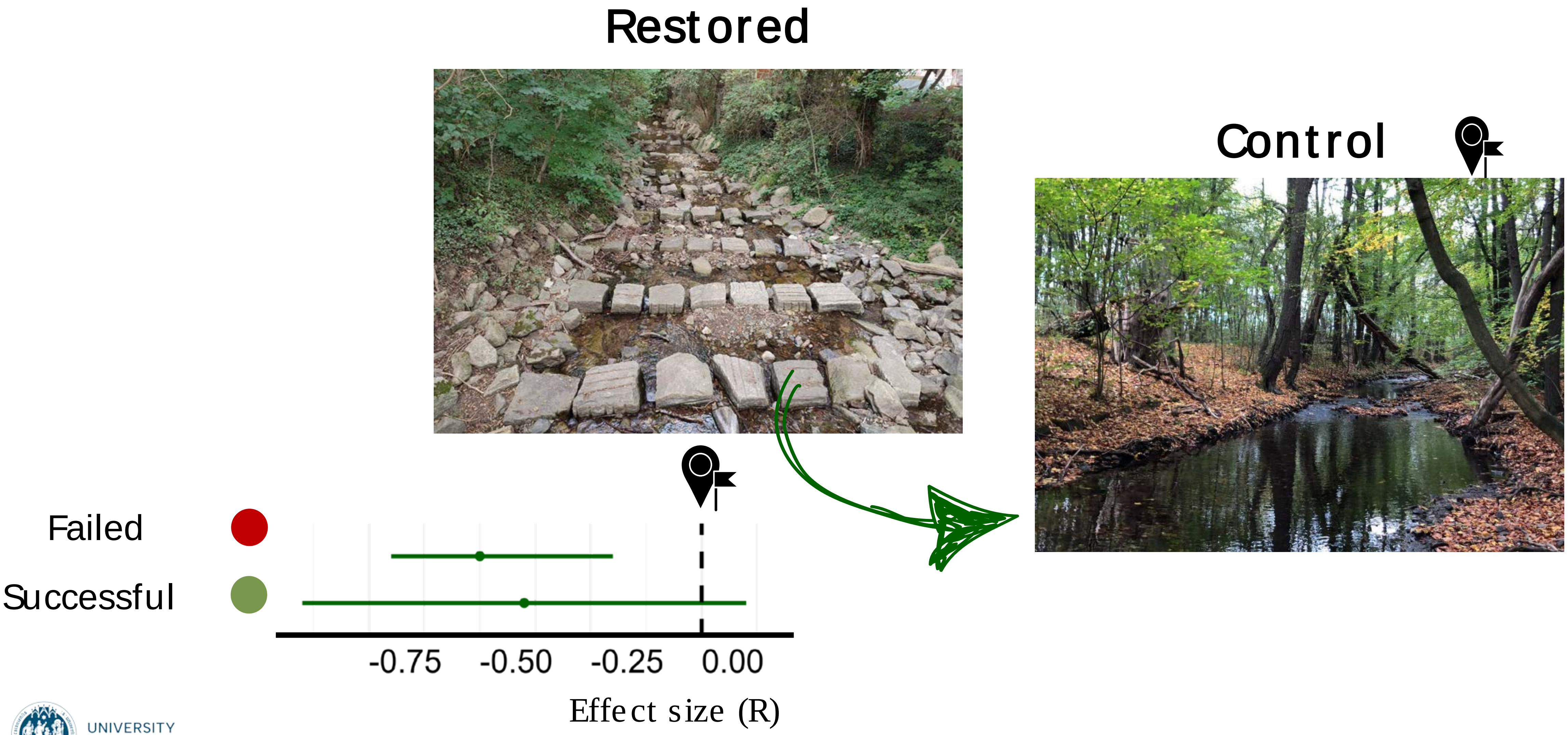


Ritort, Catalunya

General assumptions (in RESTOLINK and elsewhere):

a) Bacteria (prokaryotes) responsible for heterotrophic functions (e.g. DOC uptake)
b) Algae (eukaryotes) responsible for autotrophic functions (e.g. photosynthesis)
c) Both pro- and eukaryotes contribute to nutrient uptake (e.g. NO_3) and metabolism

Comparison within triplets via effect sizes



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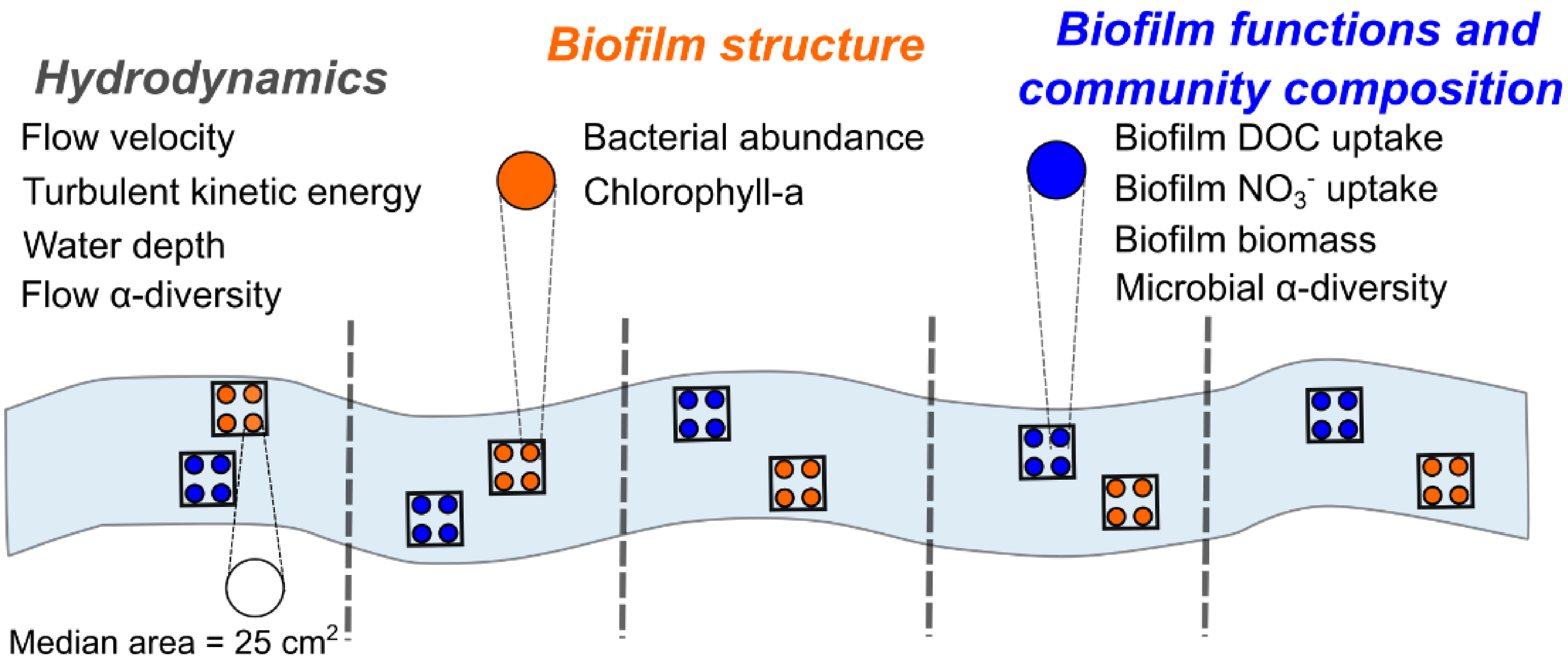
Update WP2- Microbial diversity

RESTOLINK, 13.10.2025

Julia

Sampling strategy



Data status

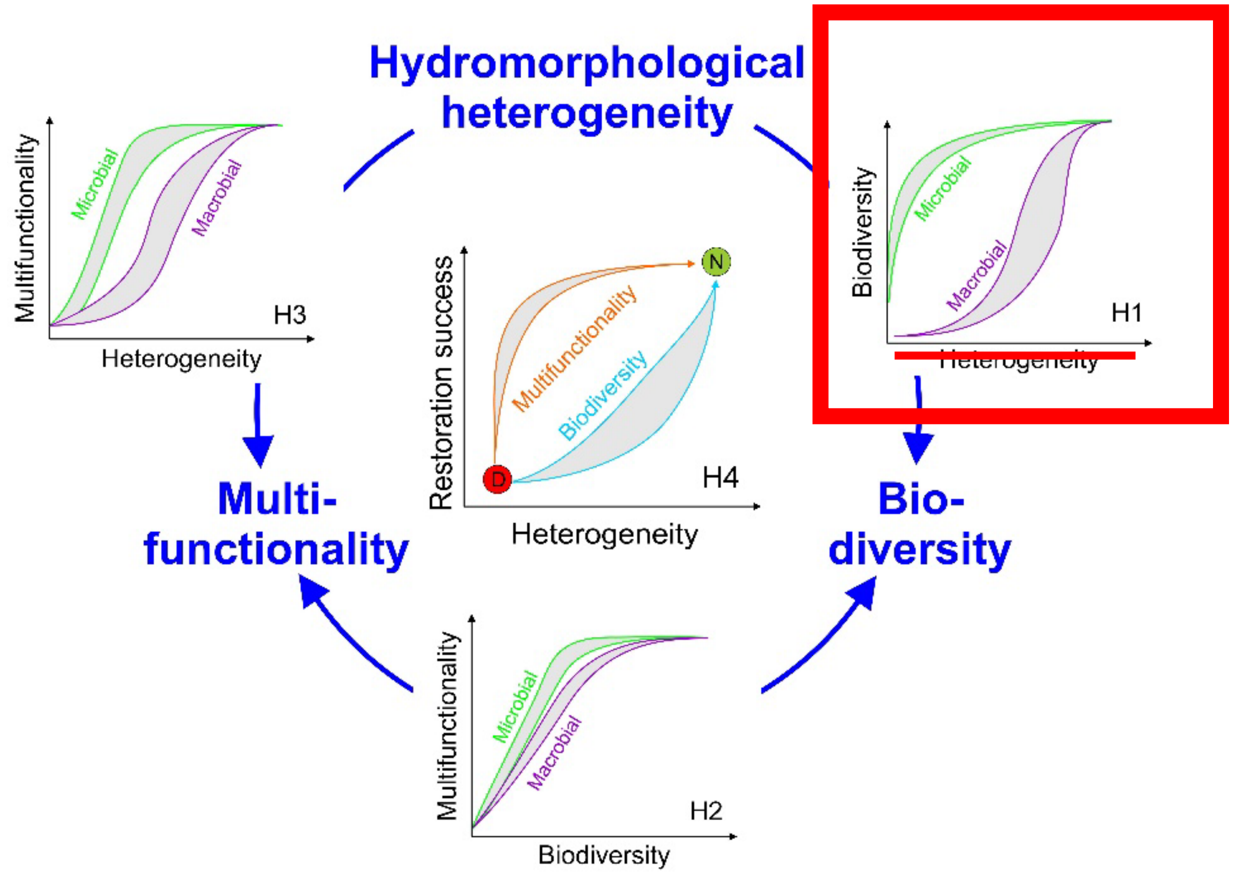
Country	Triplette	Site	16S	n	18S
GERMANY	Ecker	Impacted	analyzed	12	sequenced
		Control	analyzed	20	
		Restored	analyzed	20	sequenced
	Holtemme	Impacted	NA	0	sequenced
		Control	analyzed	8	
		Restored	analyzed	10	sequenced
	Ilse	Impacted	NA	0	sequenced
		Control	analyzed	10	
		Restored	analyzed	10	sequenced
SPAIN	Riera Major	Impacted	NA	0	sequenced
		Control	analyzed	6	
		Restored	analyzed	10	sequenced
	Ritort	Impacted	NA	0	
		Control	analyzed	10	sequenced
		Restored	analyzed	10	sequenced
	Sorreigs	Impacted	NA	0	
		Control	analyzed	10	
		Restored	analyzed	9	
BRASIL	Brasil 1	Impacted	NA		sequenced
		Control	Sequencing failed		sequenced
		Restored	Sequencing failed		
	Brasil 2	Impacted	NA		
		Control	Sequencing failed		sequenced
		Restored	Sequencing failed		sequenced
	Brasil 3	Impacted			
		Control	PCR process		
		Restored			

Steps:

- Extraction
- PCR
- Sequencing
- Data analysis

Only Control-Restored comparisons are possible

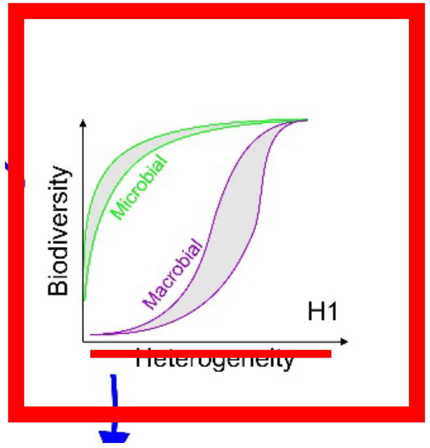
Hypothesis H1



H1: **Biodiversity** is generally **positively related to hydromorphological heterogeneity** for microorganisms.

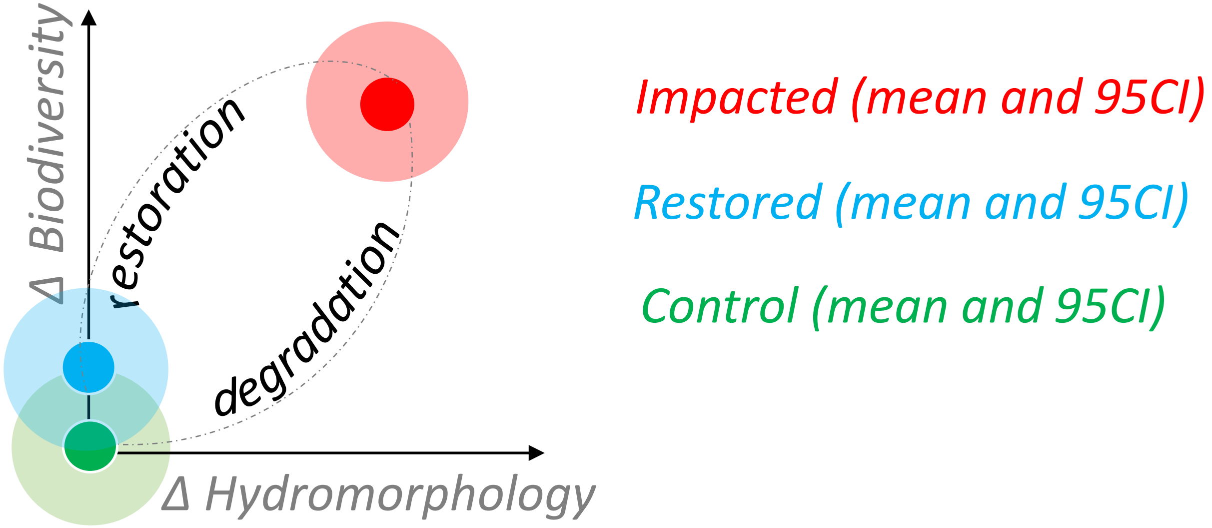
We measured more than heterogeneity. We moved from a heterogeneity-based hypothesis to one focused on ***matching*** *the hydromorphological conditions in the control-site (more a restoration approach)*

New Hypothesis (H1)



If restoration restores the hydrodynamics to levels similar to those of the control reach, this will promote the recovery of the microbial diversity.

We could proof this hypothesis with the 16S and hydrodynamics datasets from Germany and Spain.



Δ = Deviation from the control conditions

Hydrodynamics mostly recover for Germany

		Germany			Spain		
	Parameter	Ecker	Holtemme	Ilse	Riera M	Soreis	Ritort
Hydromorphology	Turbulent kinetic energy	Recovered	no	Recovered	?	?	?
	Flow velocity	Recovered	Recovered	Recovered	?	?	?
	Flow alpha diversity	Recovered	Recovered	Recovered	?	?	?

Microbial α-diversity mostly recover for both countries

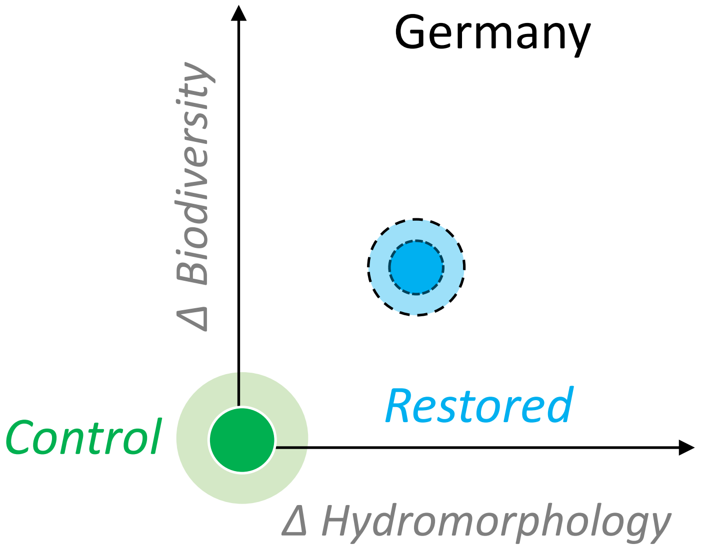
		Germany			Spain		
	Parameter	Ecker	Holtemme	Ilse	Riera M	Soreis	Ritort
Hydromorphology	Turbulent kinetic energy	Recovered	no	Recovered	?	?	?
	Flow velocity	Recovered	Recovered	Recovered	?	?	?
	Flow alpha diversity	Recovered	Recovered	Recovered	?	?	?
Diversity	Microbial Richness	Recovered	Recovered	Recovered	Recovered	Recovered	Recovered
	Microbial Eveness	Recovered	Recovered	Recovered	Recovered	Recovered	Recovered
	Beta diversity	no	no	no	Recovered	Recovered	Recovered

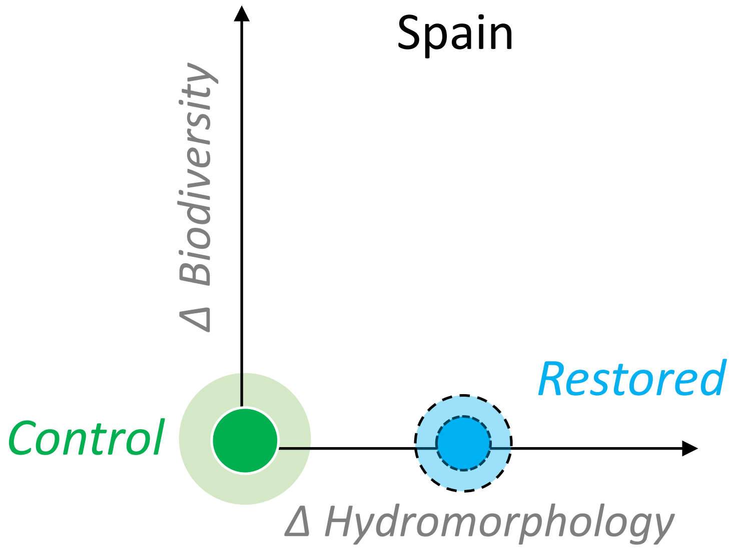
Drivers (results from the glm model)

Parameter	Factors	ANOVA	Relationship
Microbial diversity (alpha)	**Turbulent kinetic energy**	***	Positive
	Stream	***	
	Stream x Canopy	*	
Bacteria abundance	**Turbulent kinetic energy**	**	Negative
	Stream	***	
Biofilm biomass	TKE	***	Negative
	Stream	***	
	Canopy	**	Negative
	Stream x **FlowAlpha**	**	
Chlorophyll-a	Stream	***	
	Stream x Canopy	**	

Take Home Message

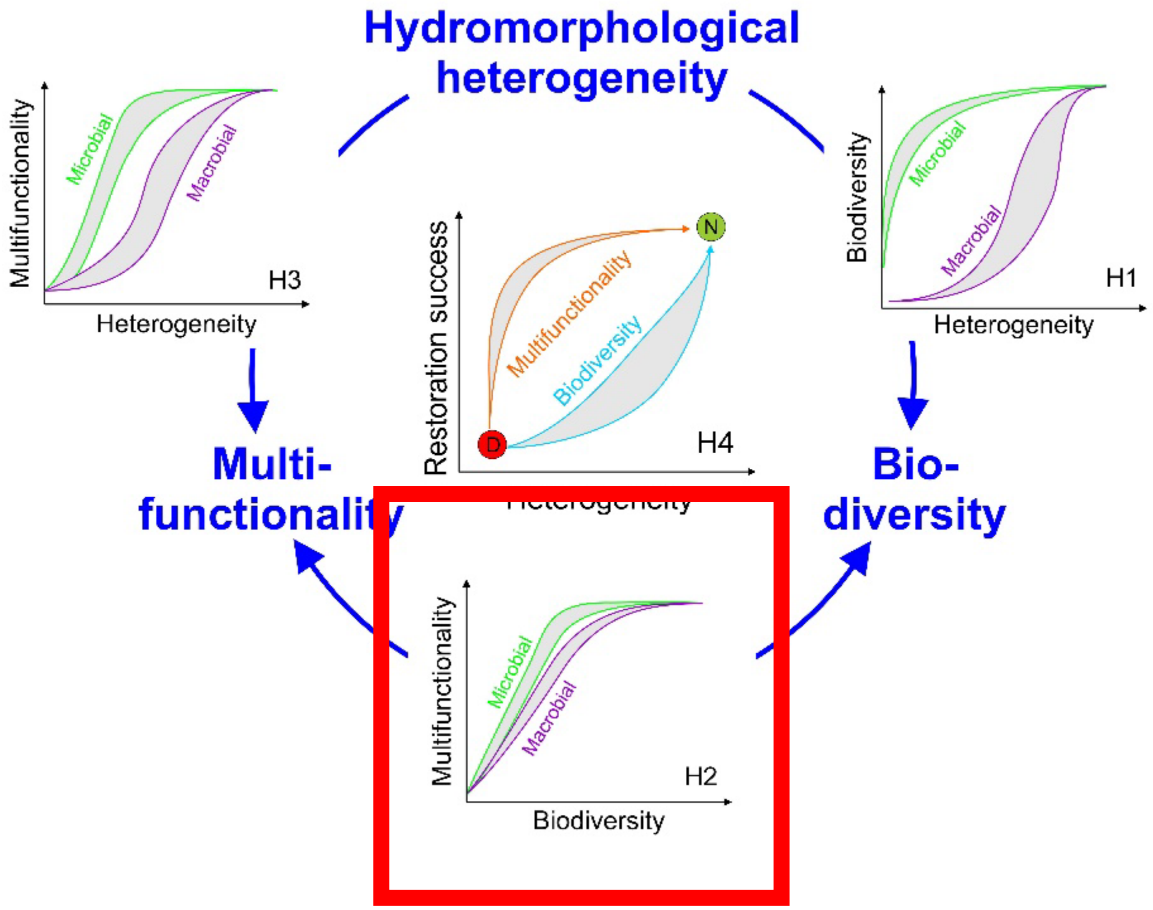
- Restoration of small-scale hydromorphology lead to recovery of **microbial α-div in all German streams. → Also in Spain?**





Q1: Do we want to proceed with that?

Hypothesis H2



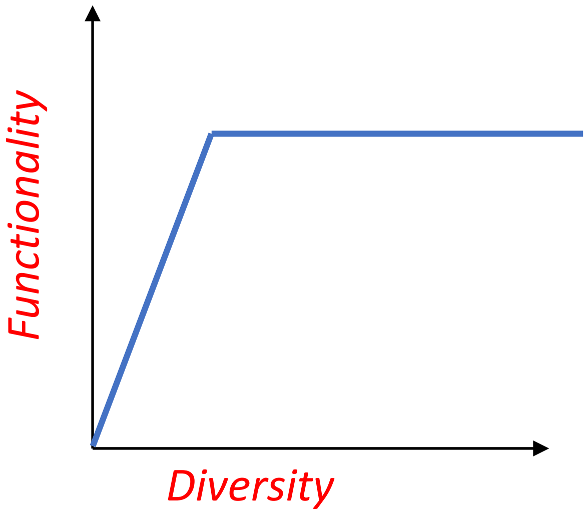
H2: **Biodiversity** scales asymptotically with **multifunctionality** because **few species contribute disproportionately** to ecosystem functioning.

- **Multi**functionality (how to quantify it)?

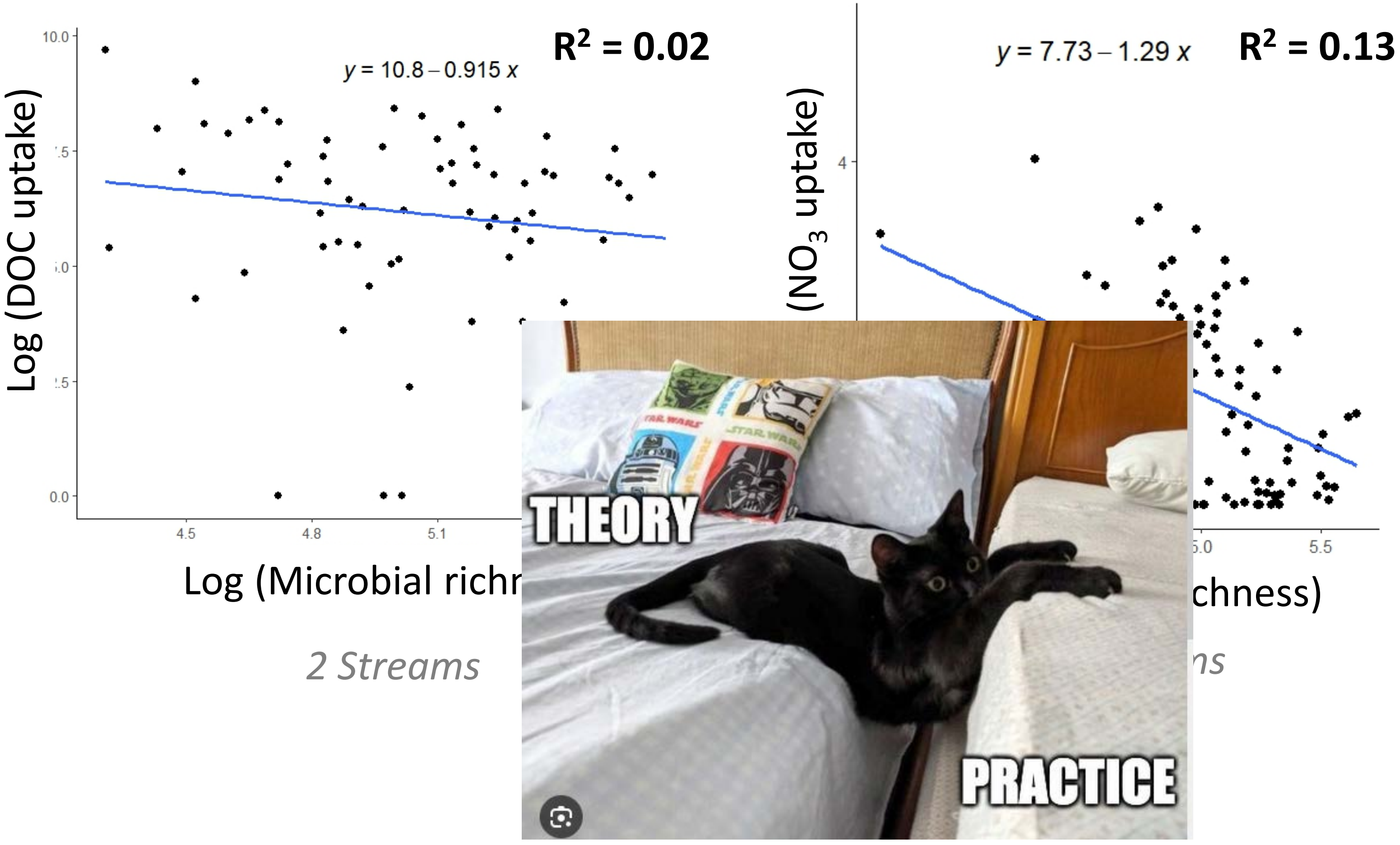
  Approach:Assess relationship between diversity-functioning

Assess diversity-functioning relationship

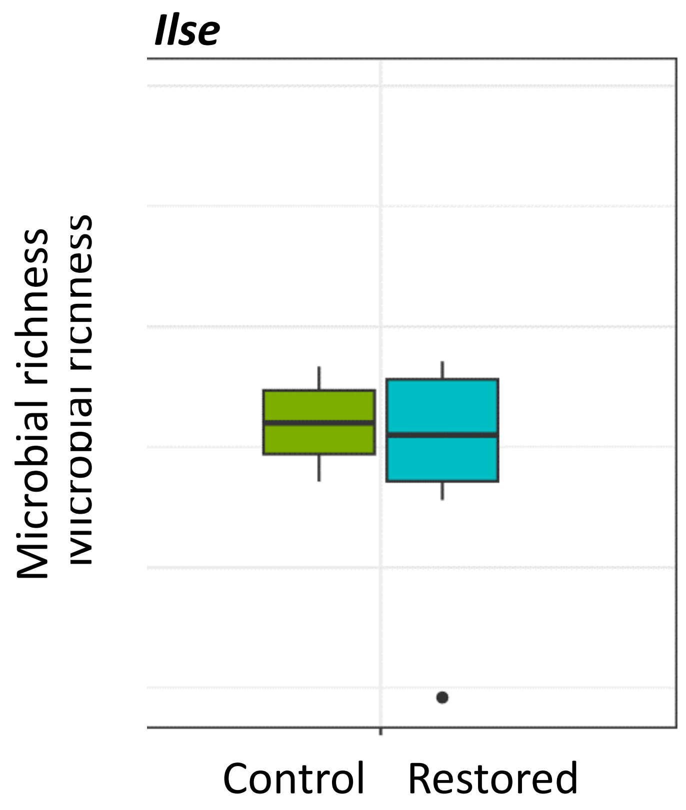
Theory

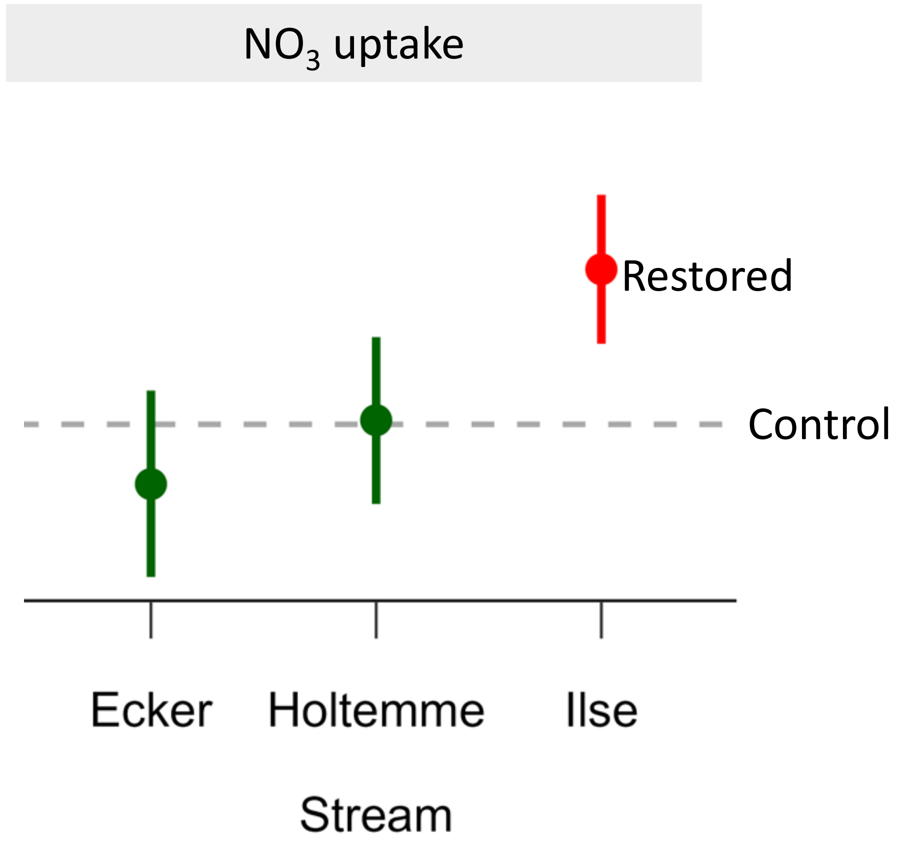


Practice



Does restoring diversity ensure the restoration of functionality? Not always…





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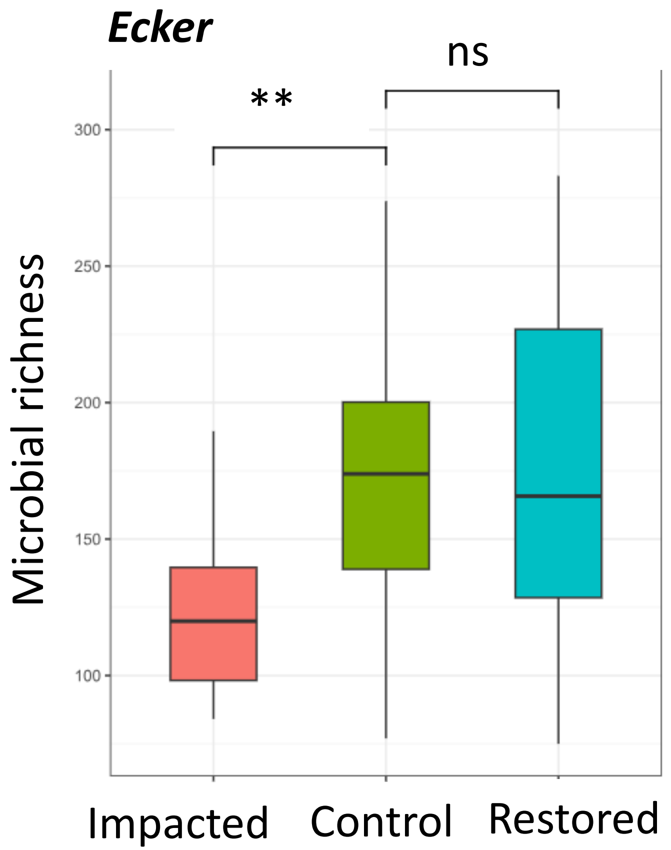
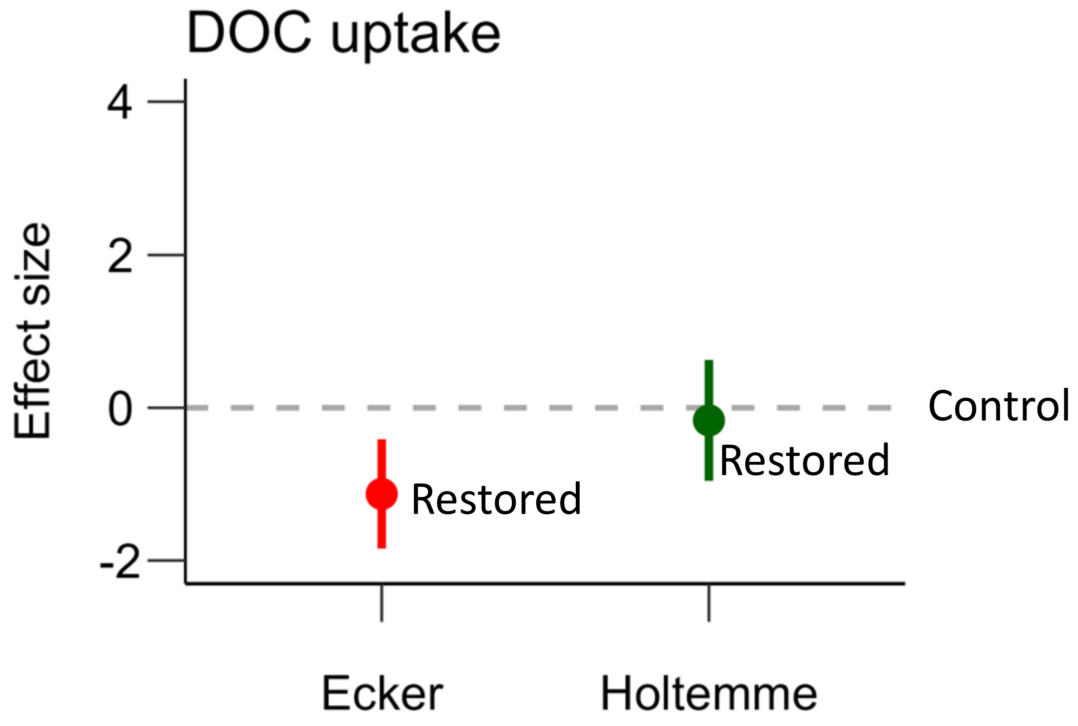
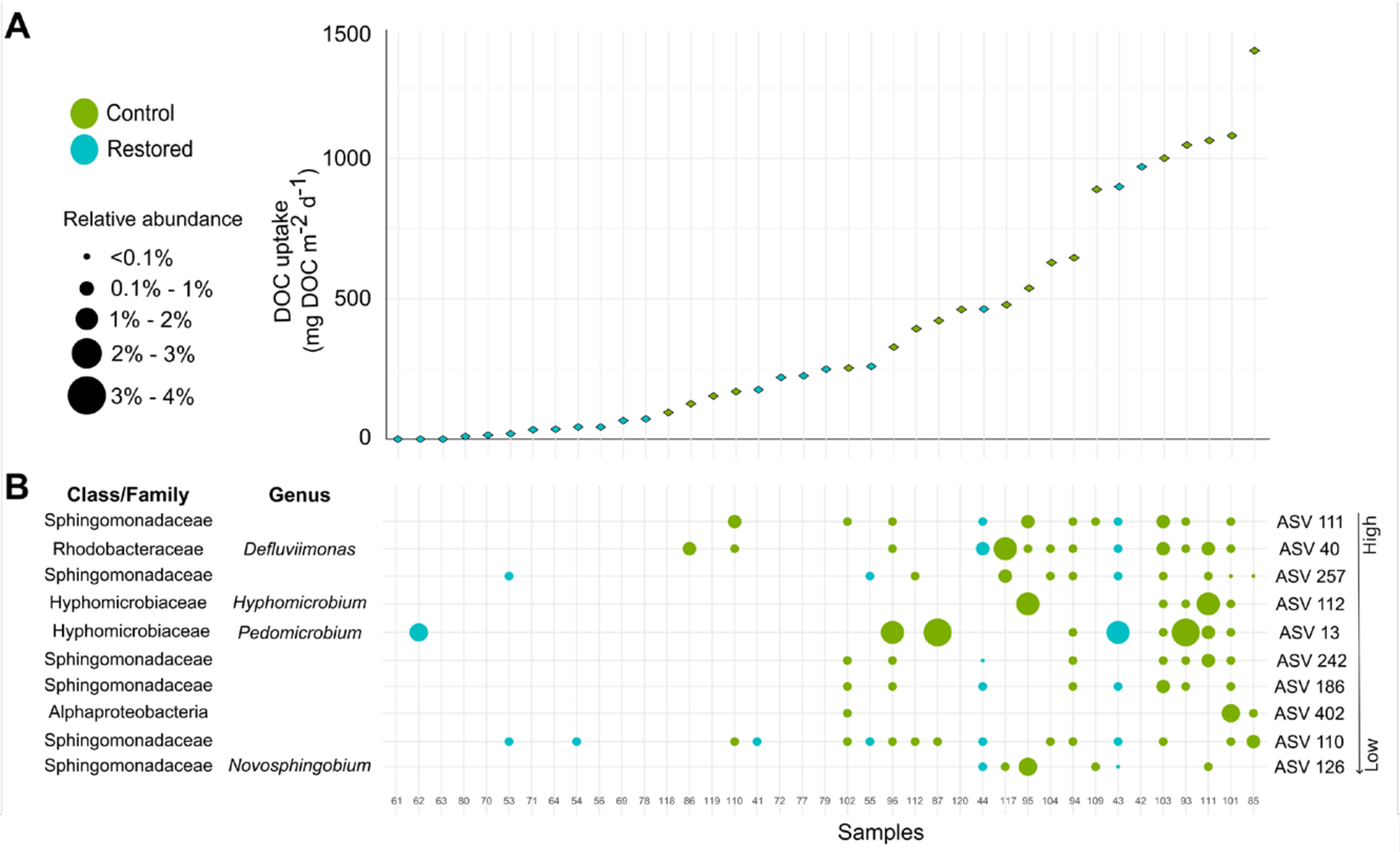




…despite richness is comparable, few species contribute mostly to functionality → incomplete recovery of DOC



Take Home Message

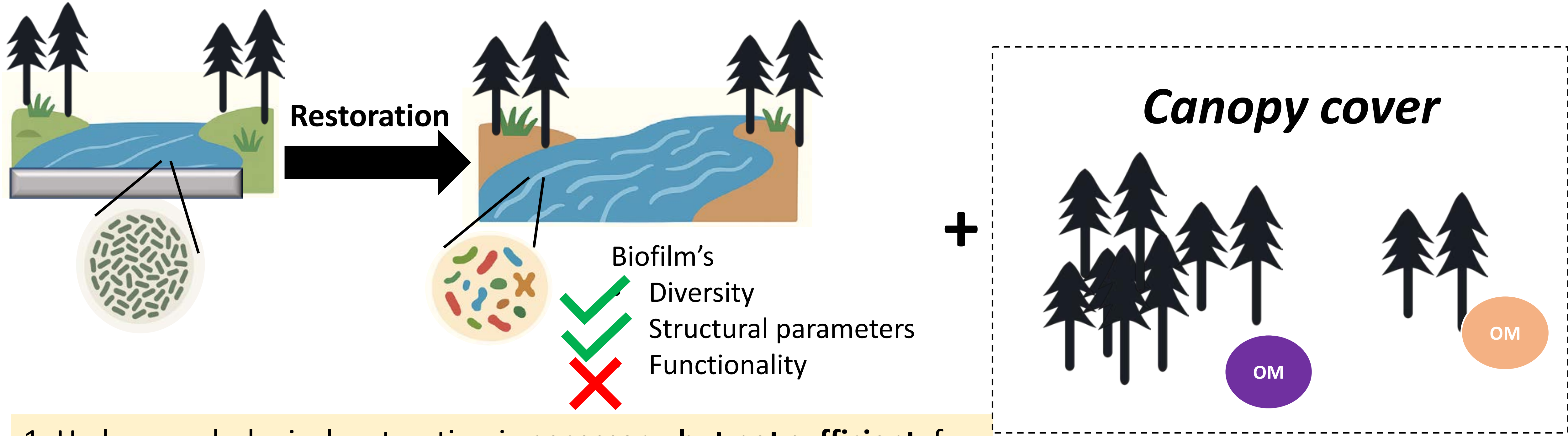
Hydromorphological restoration lead to recovery of **microbial α-div in all German streams** (Table 1), **but it seems that this does not guarantee functional recovery** (Table 2).

This may be due to the fact that ecosystem functions are performed by a few key taxa rather than the entire community (Fig. 1).

Other factors influence microbial functioning

Final model	Factors	ANOVA	Relationship
NO_3 uptake	Flow alpha diversity	**	Negative
	Canopy cover	***	Negative
DOC uptake	Stream		
	Flow alpha diversity	***	Negative
	Canopy cover	**	Negative

Take Home message:



1. Hydromorphological restoration is **necessary, but not sufficient**, for the recovery of biofilm's functionality.

2. **Few taxa** are responsabile for the functions we measured.

3. Other factors such as **canopy cover** or **organic matter composition** can affect biofilm's functionality by modulating **energy (C & light) sources.**

WP 3: Food webs

Overarching aim and method

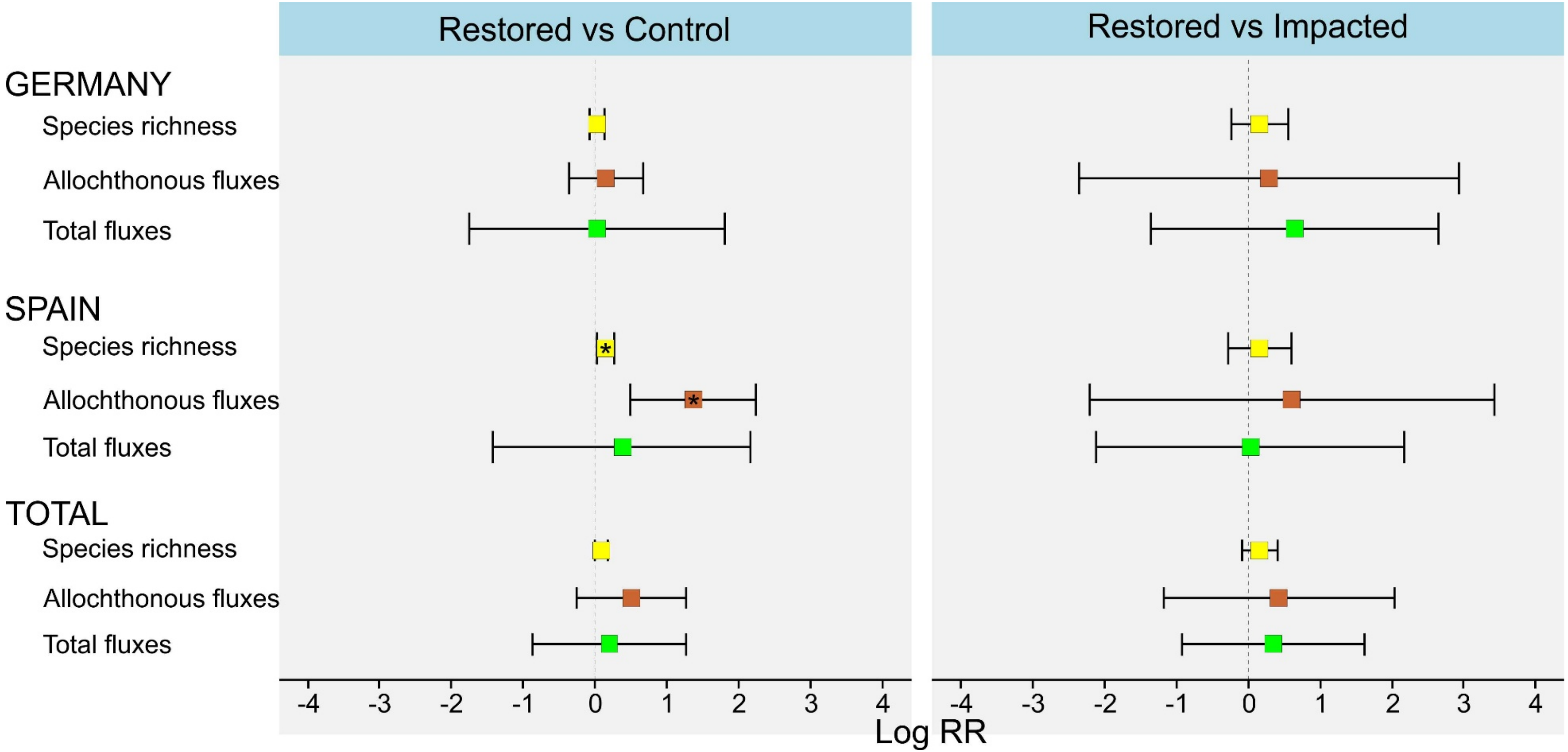
Aim

- Analyze if food web structure and OM fluxes can be restored
- Test if hydromorphology and species richness are dominant drivers of food web structure and fluxes
- Quantify if restoration success is related to biomes

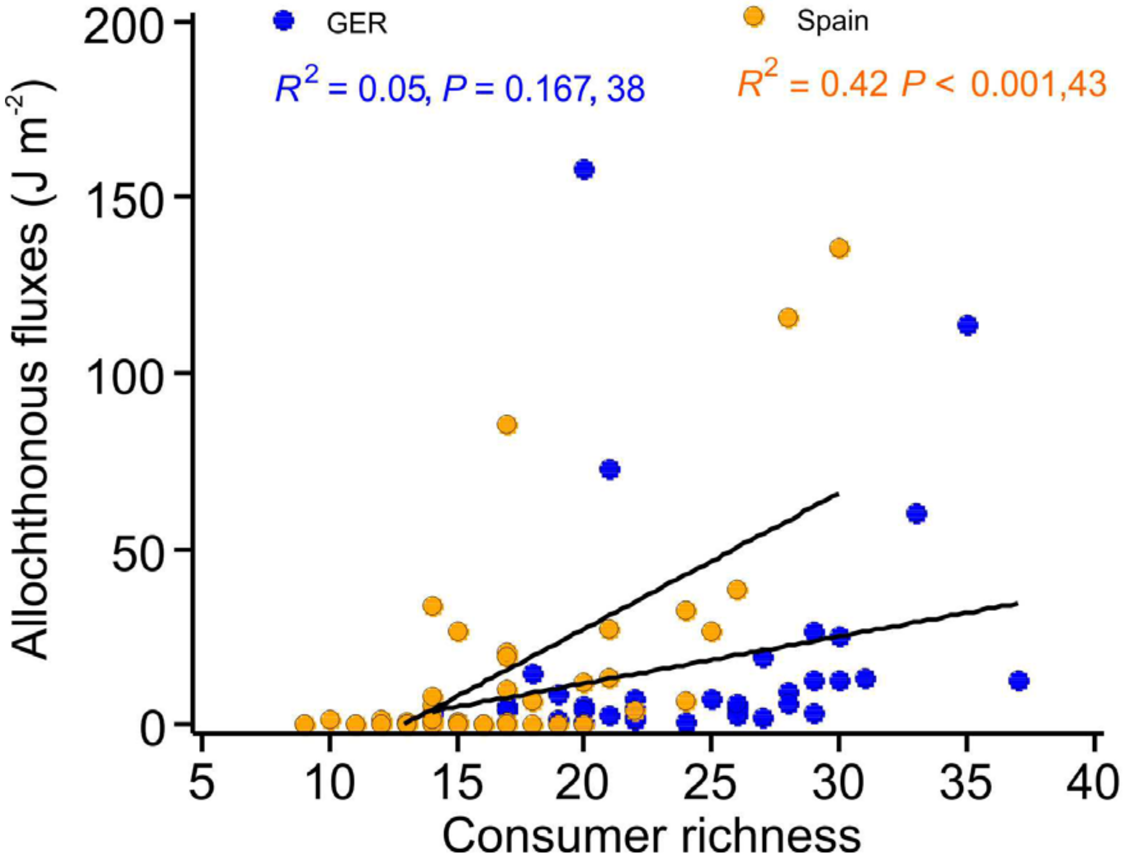
Approach

- Invertebrate samples from red patches → body weight, and functional feeding groups
- Invertebrate samples from green patches → mixing model for dietary contributions
- Food web construction using the flux-web approach: allometric approach to estimate energy fluxes through webs
- Calculate log ratios for Restored:Control and Restored:Impact at patch scale

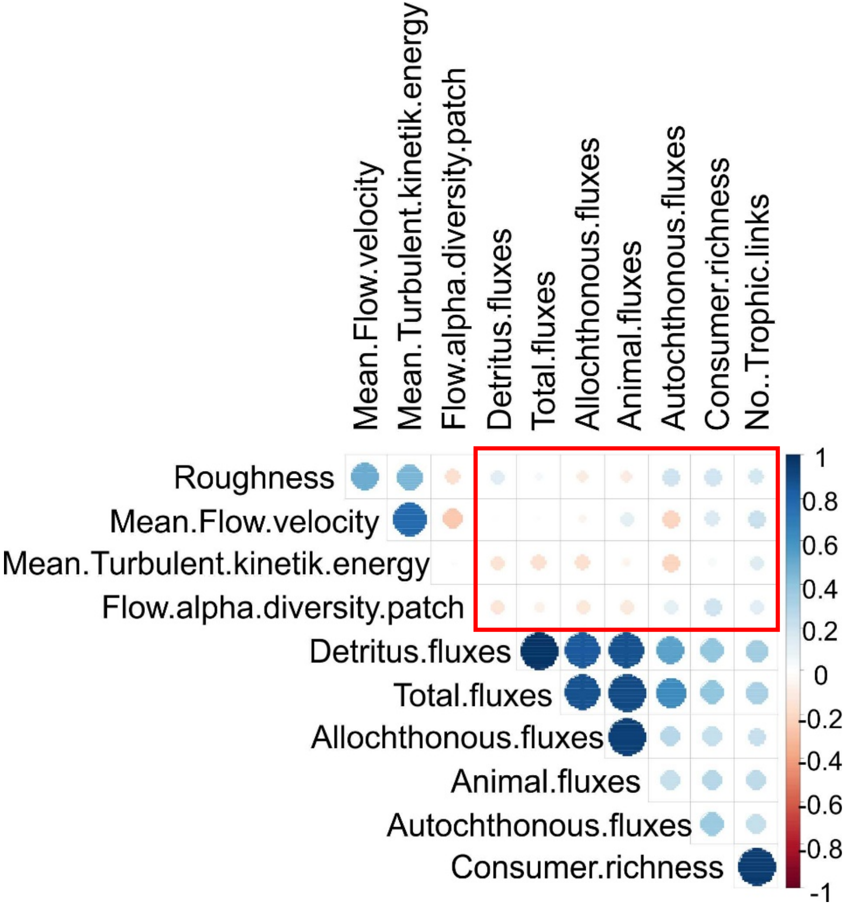
Restoration success



Diversity-function relationship



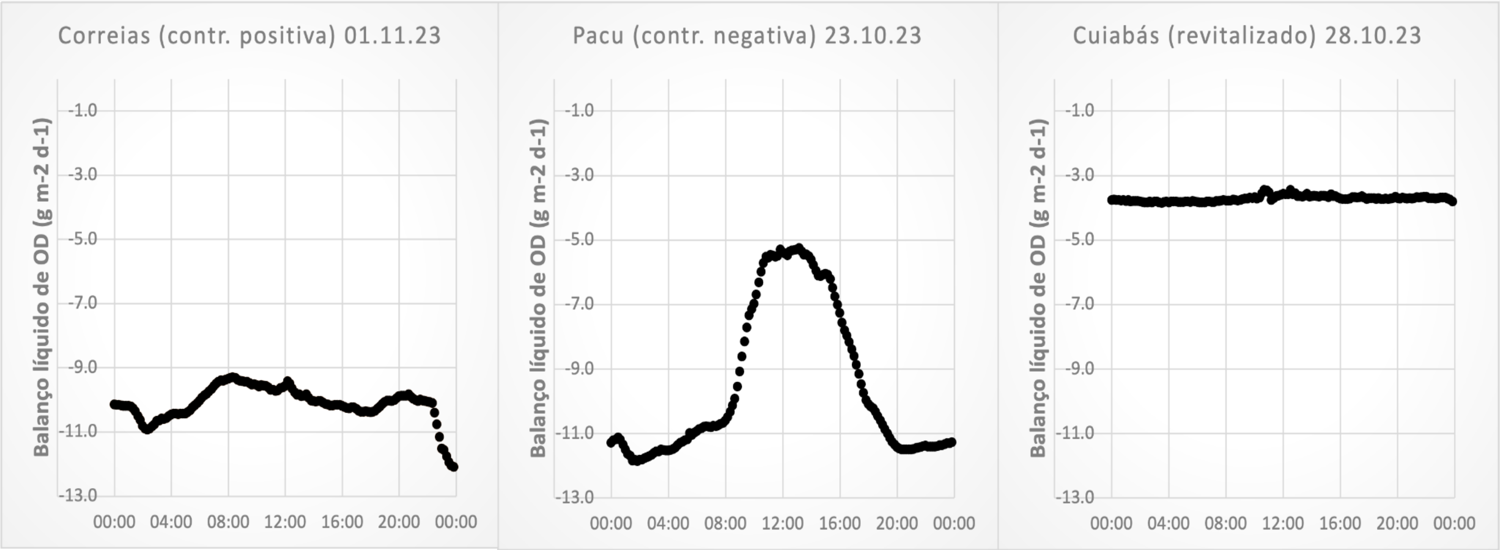
Does hydromorphology determine food web properties?



Summary

- Species richness, food web structure, and fluxes can be restored concurrently
- Relationship between biodiversity and ecosystem functions for food webs depends on country (biome?)
- Richness and food web parameters are uncorrelated = complementary indicators (at least in Germany)
- Hydromorphology seems not to be responsible for restoration effects in German streams
- BRA and SWE data needed to finalize statistics
- Requires 2 weeks if all data are quality-checked and ready for analysis
- Product: synthesis paper on biodiversity-food web relationship and the role of hydromorphology across countries

RESTOLINK: Preliminary results Whole-stream Metabolism



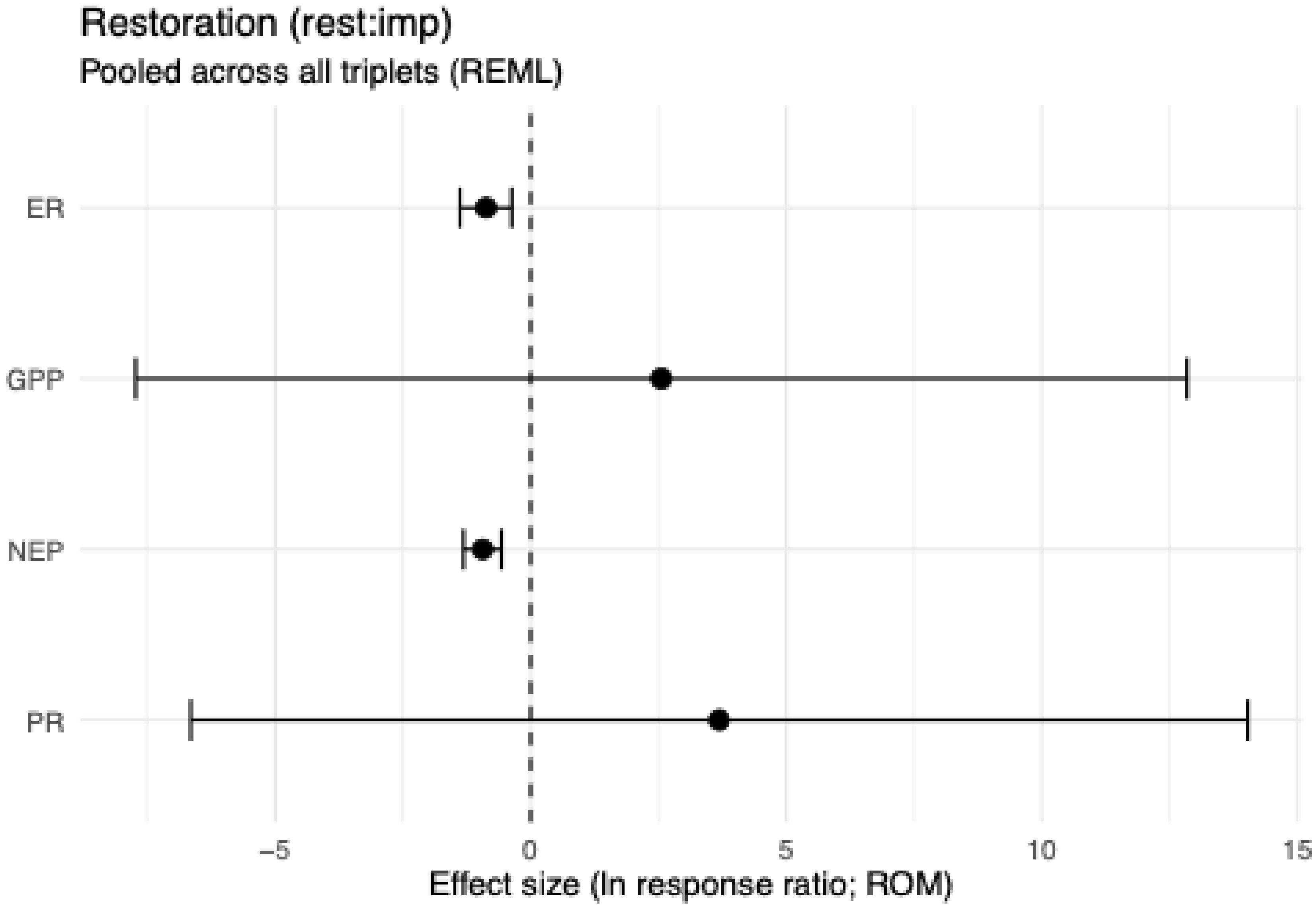
HYPOTHESIS

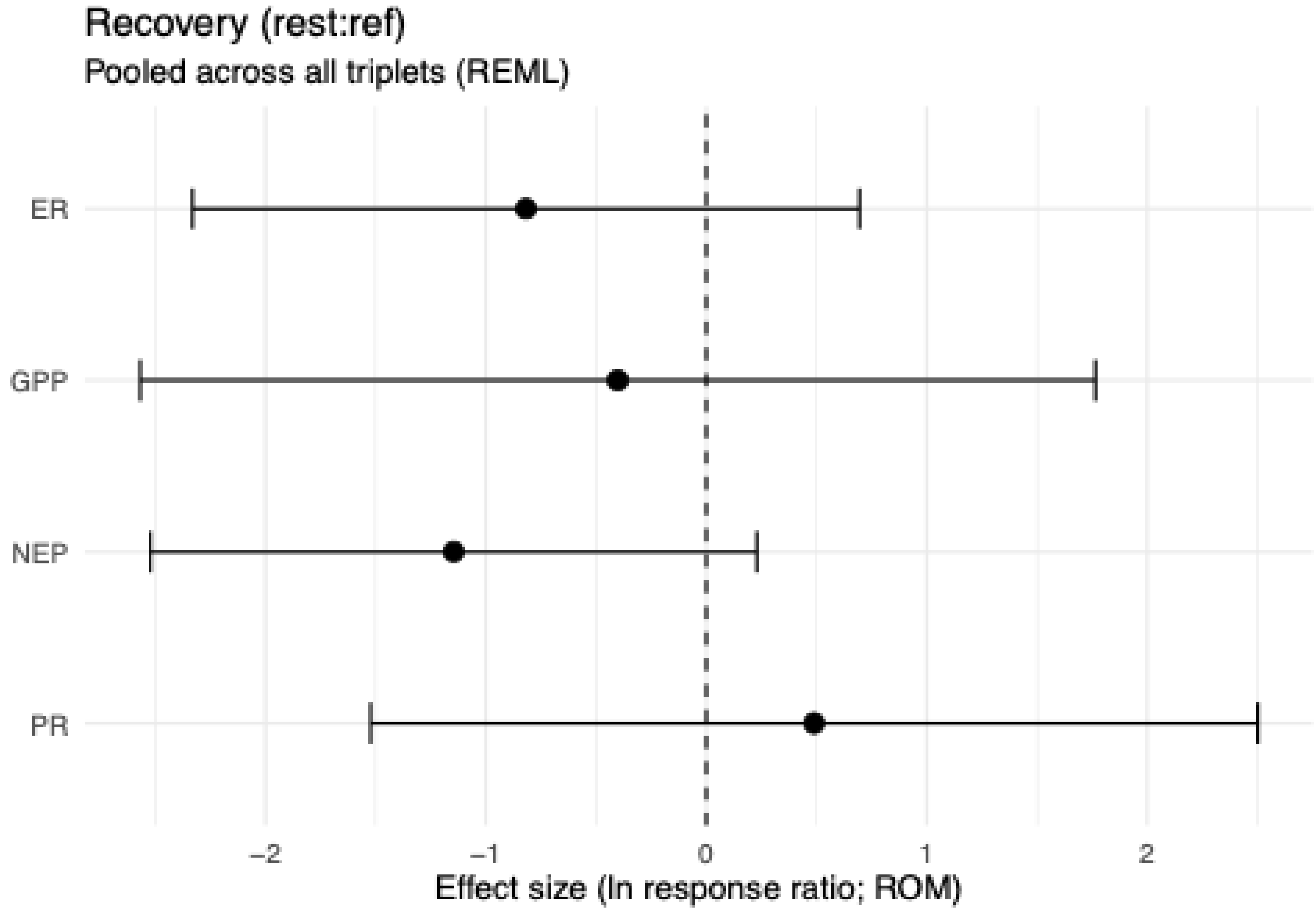
Restoration shifts metabolic rates from those of impacted streams closer to those of reference streams (-> triplet study design)

➔ Restored streams with lower GPP (reforestation of rip. veg.) than impacted streams

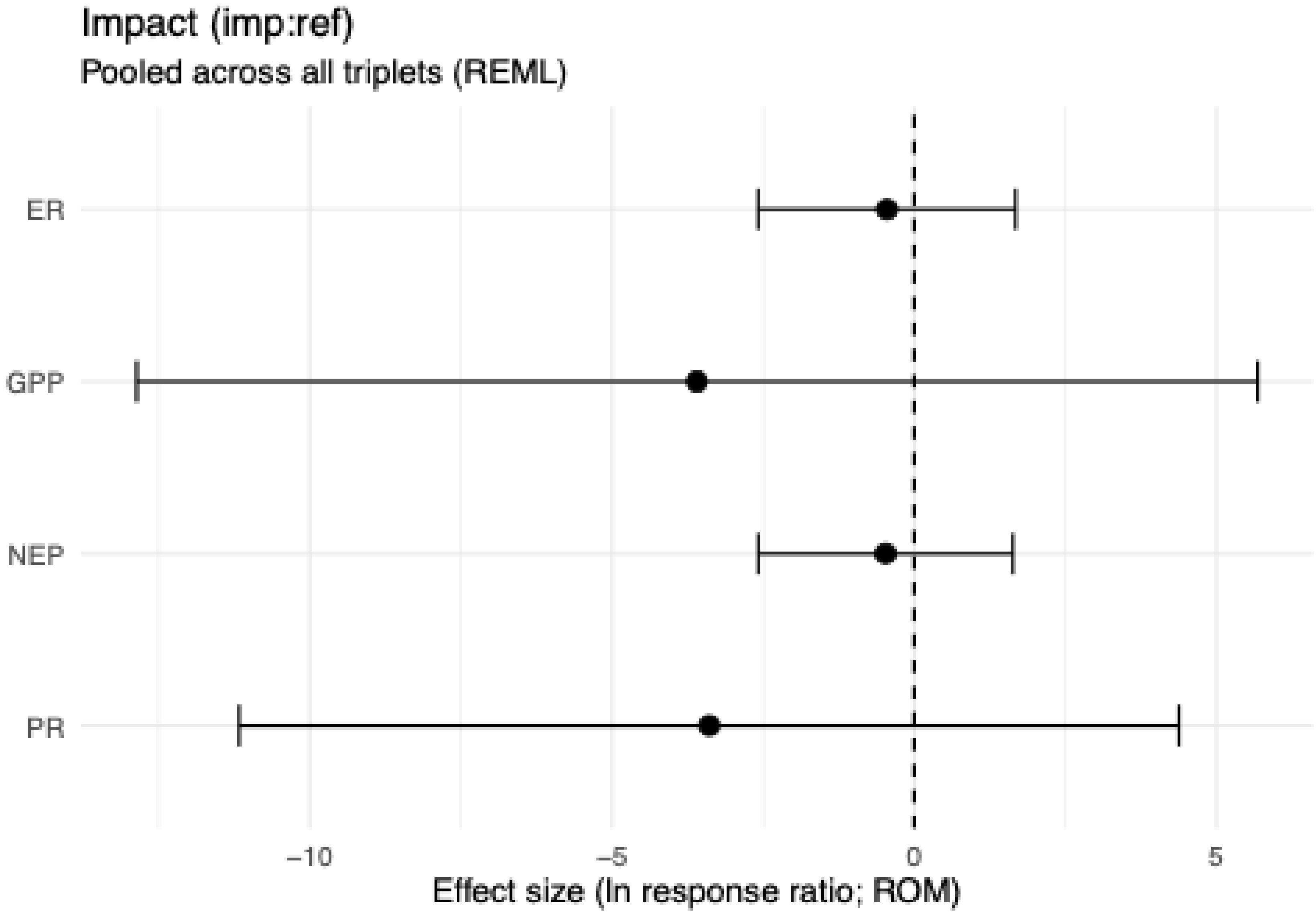
➔ Restored streams with lower ER (dam removal, pollution control) or higher ER (restoration of CPOM inputs and coarser sediment)


Restored
Positive control
Negative control

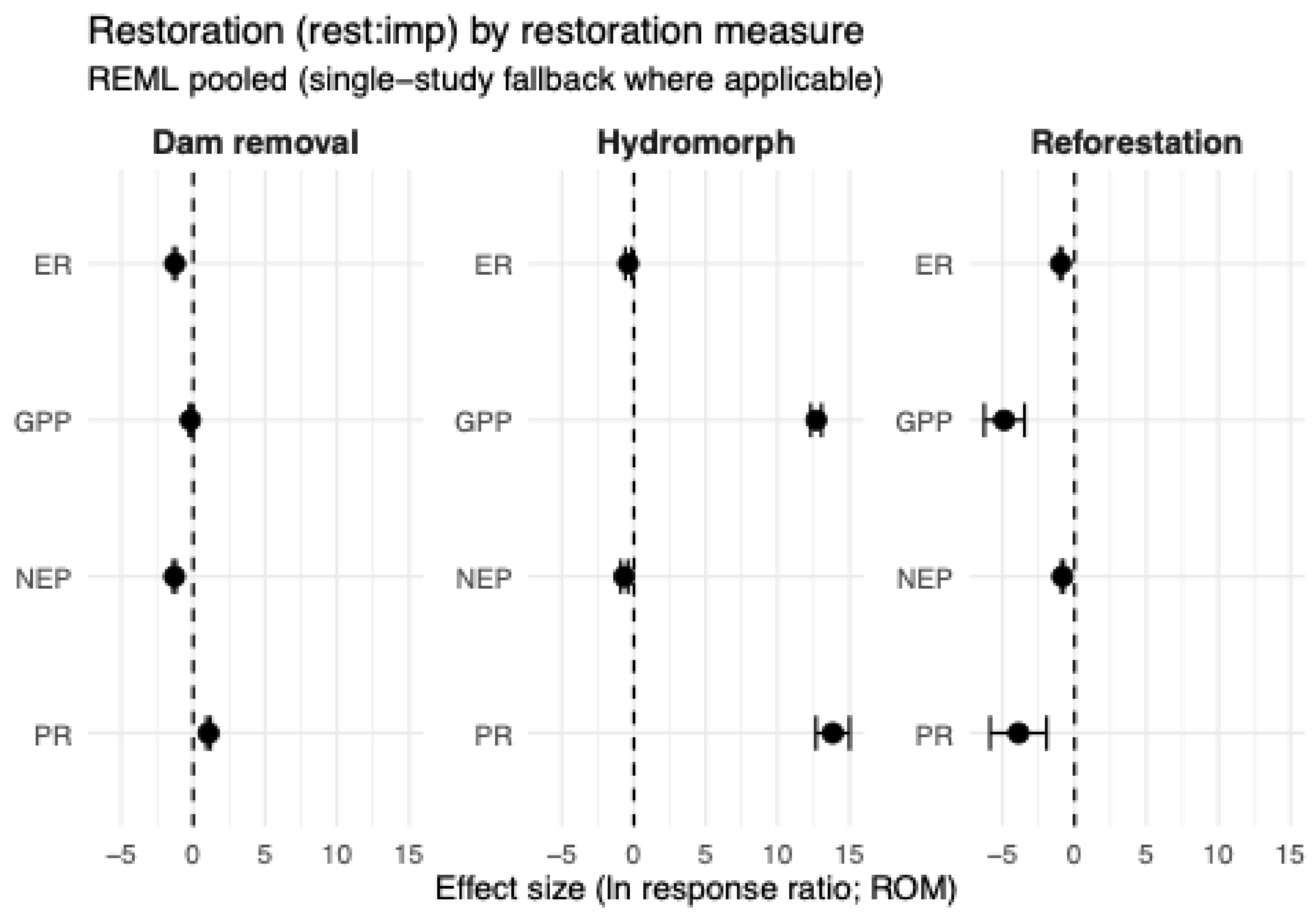

Restoration (rest:imp)
Pooled across all triplets (REML)
ER
GPP
NEP
PR
−5
0
5
10
15
Effect size (ln response ratio; ROM)



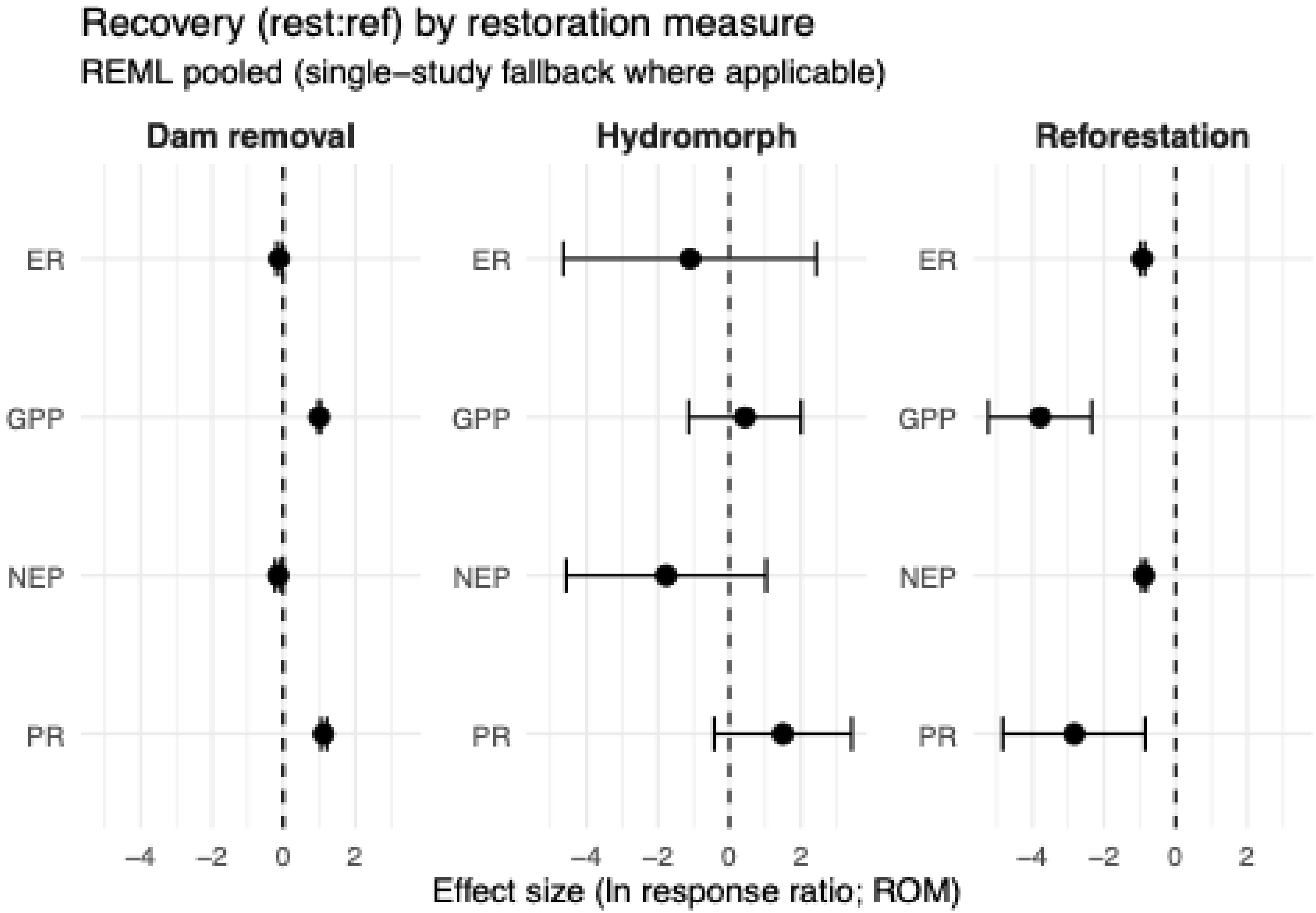
Recovery (rest:ref)
Pooled across all triplets (REML)
ER
GPP
NEP
PR
−2
−1
0
1
2
Effect size (ln response ratio; ROM)

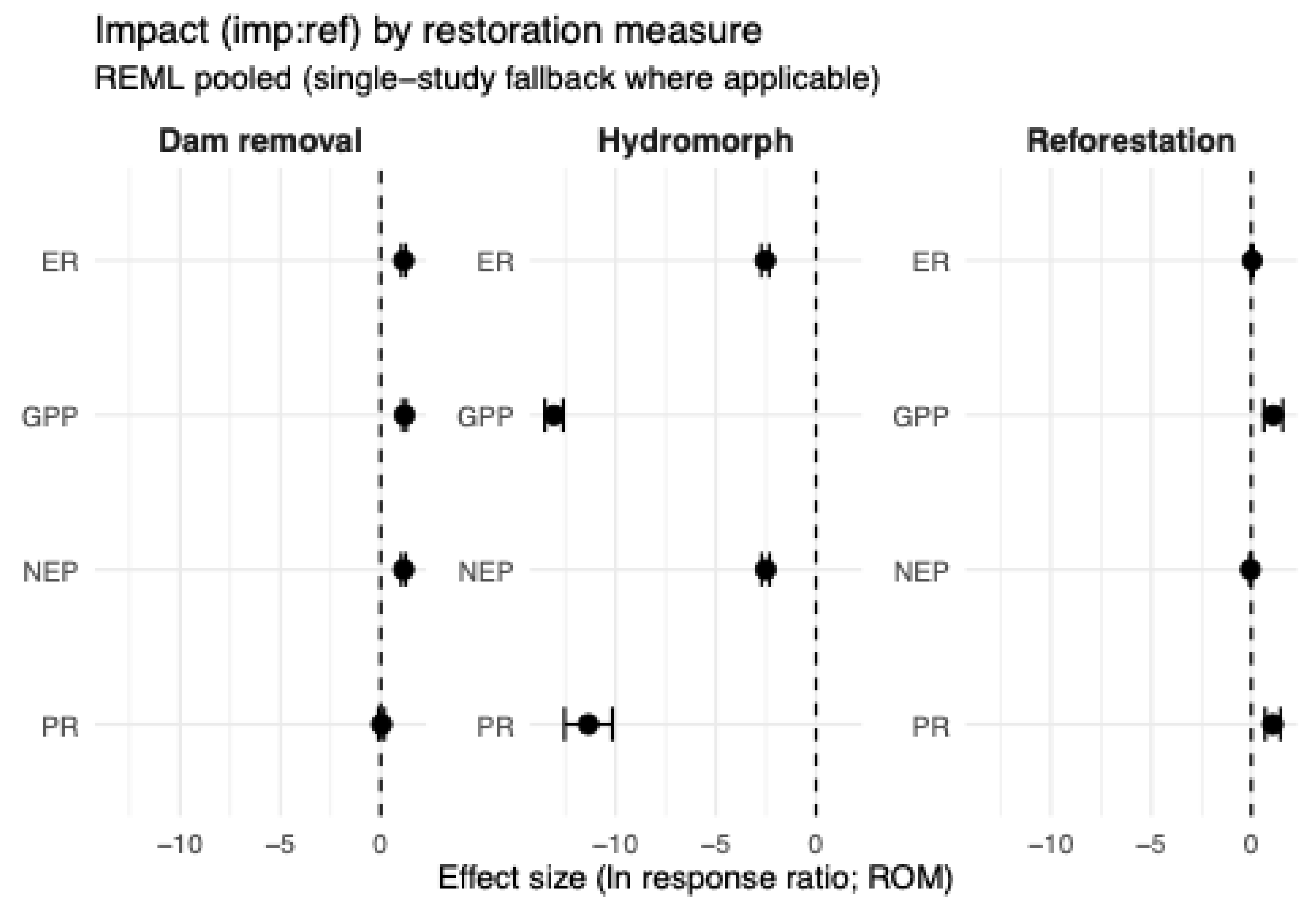


Impact (imp:ref)
Pooled across all triplets (REML)
ER
GPP
NEP
PR
−10
−5
0
5
Effect size (ln response ratio; ROM)

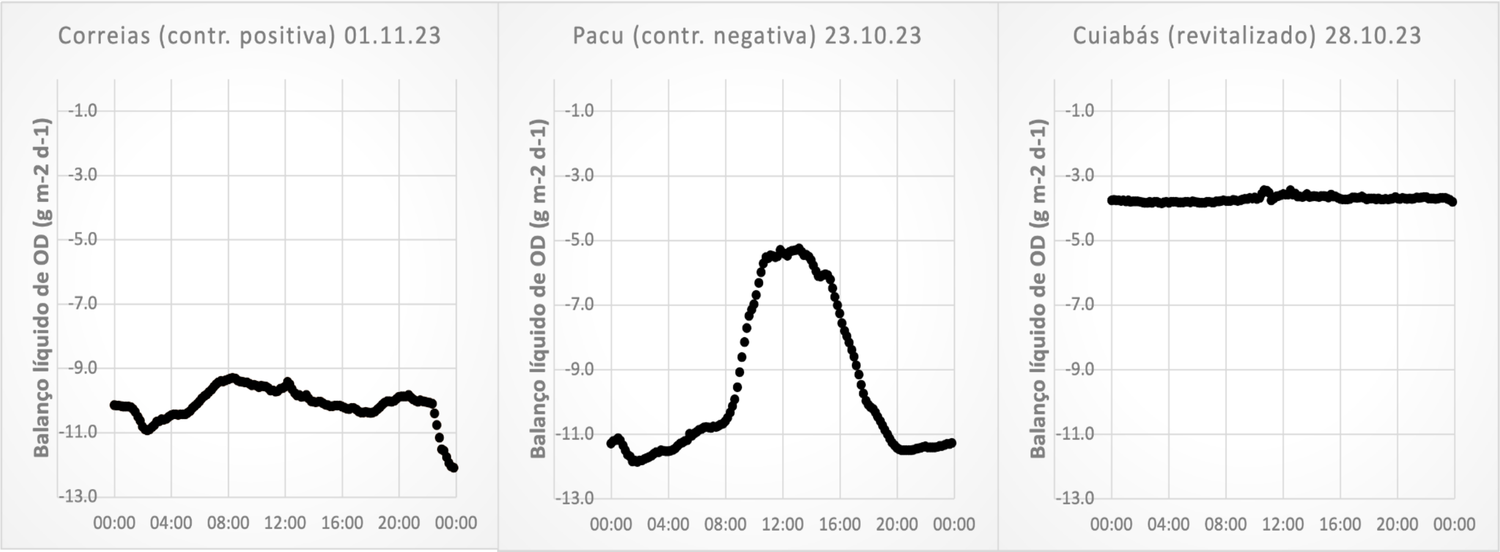


Restoration (rest:imp) by restoration measure
REML pooled (single–study fallback where applicable)
Dam removal
Hydromorph
Reforestation
ER
GPP
NEP
PR
–5
0
5
10
15
Effect size (ln response ratio; ROM)


Recovery (rest:ref) by restoration measure
REML pooled (single−study fallback where applicable)
Dam removal
Hydromorph
Reforestation
ER
GPP
NEP
PR
−4
−2
0
2
Effect size (ln response ratio; ROM)


Impact (imp:ref) by restoration measure
REML pooled (single−study fallback where applicable)
Dam removal
Hydromorph
Reforestation
ER
GPP
NEP
PR
−10
−5
0
Effect size (ln response ratio; ROM)

RESTOLINK: Preliminary results Whole-stream Metabolism



CONCLUSIONS (so far)

➔ Large differences between restoration measures

➔ Hydromorphological restoration increased GPP and P:R

➔ Reforestation decreased GPP and P:R (even lower than in reference streams)

➔ Dam removal decreased ER and NEP, but increased P:R (even higher than in reference streams.

RESTOLINK: Preliminary results Decomposition

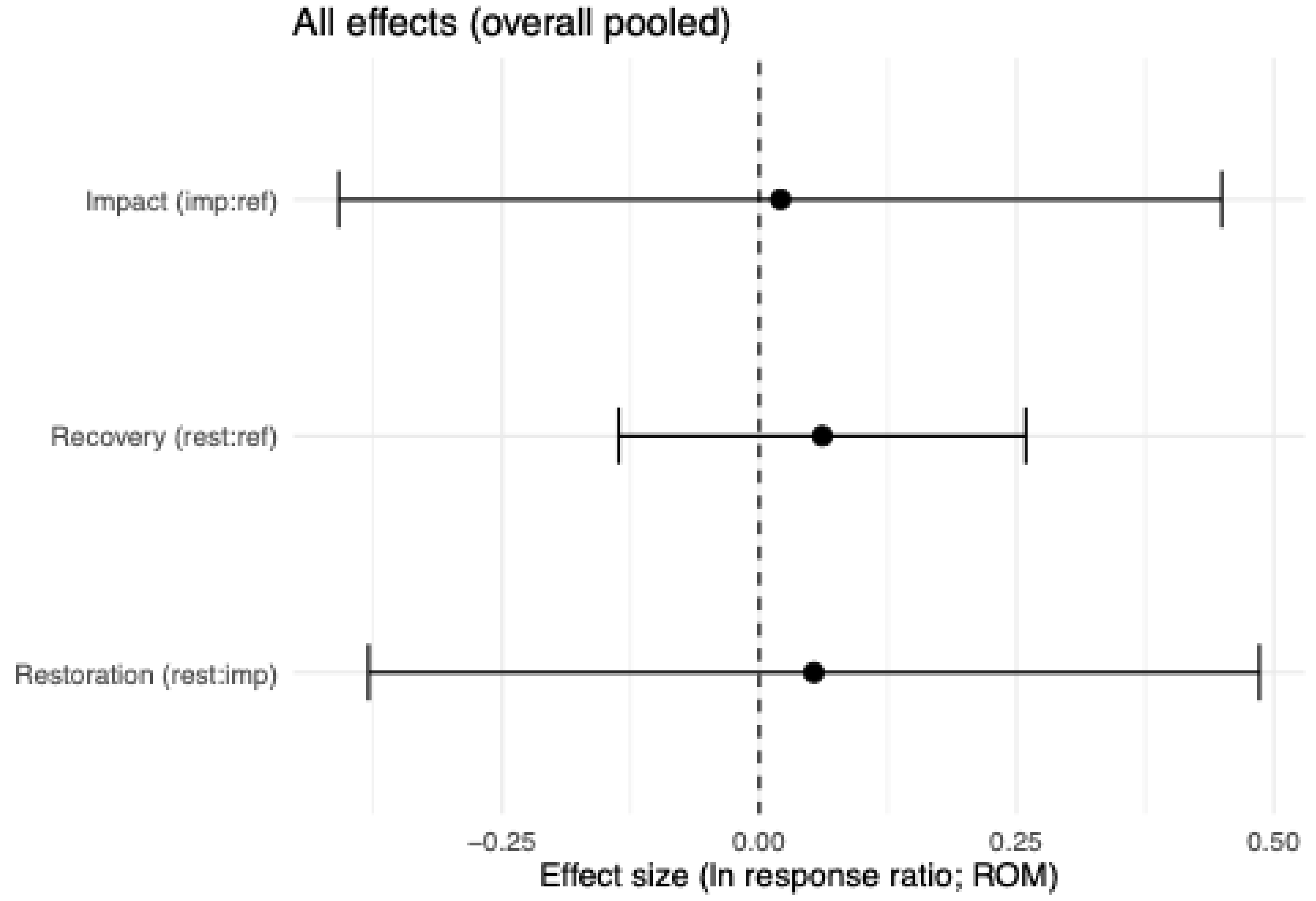
Cotton strip decomposition

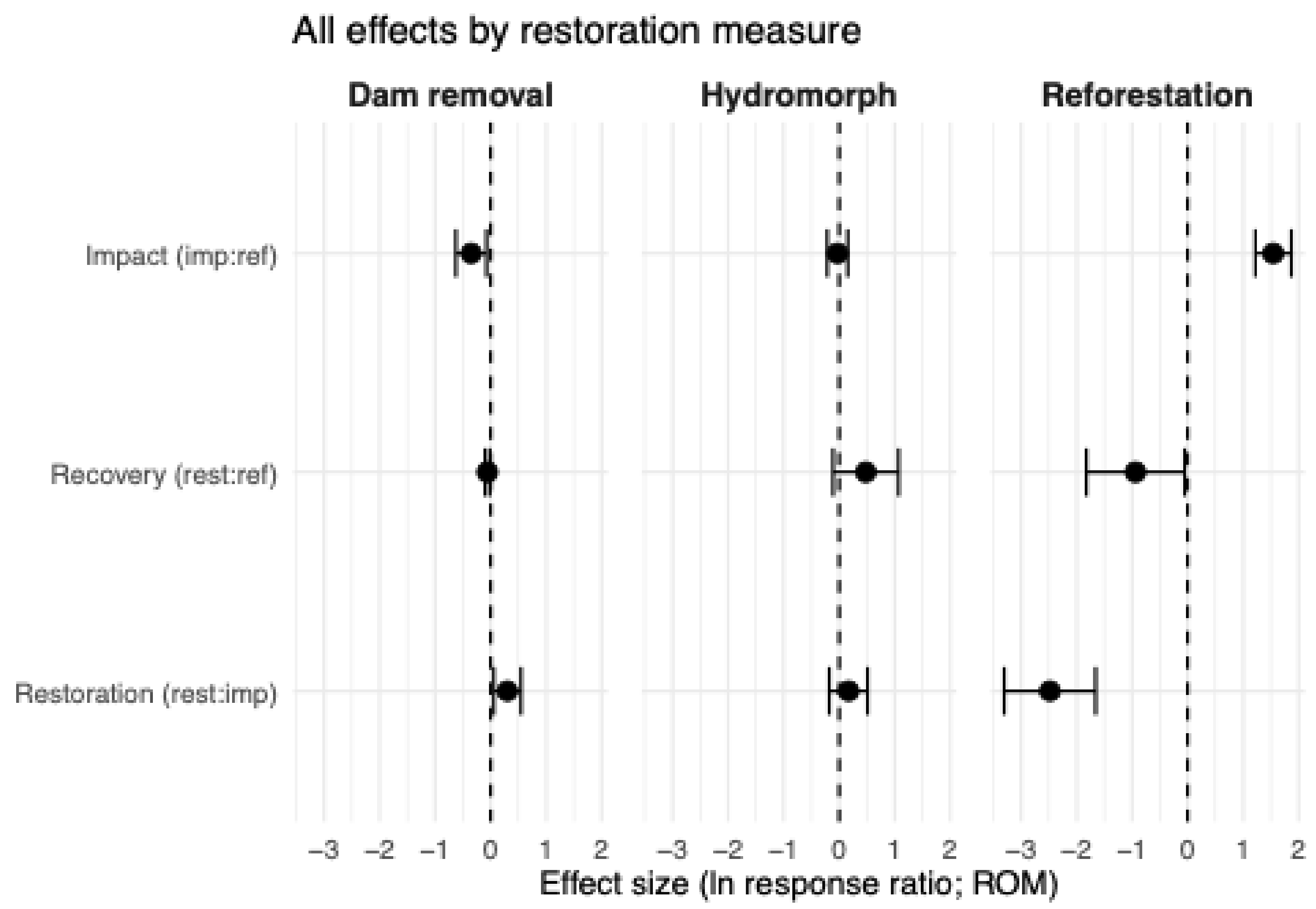
HYPOTHESIS

Restoration shifts decomposition rates from those of impacted streams closer to those of reference streams (-> triplet study design)

➔ Restored streams with higher rates (reforestation of rip. veg.; dam removal) than impacted streams; or

➔ Restored streams with lower rates (pollution control, hydromorphological restoration)


All effects (overall pooled)
Impact (imp:ref)
Recovery (rest:ref)
Restoration (rest:imp)
–0.25
0.00
0.25
0.50
Effect size (ln response ratio; ROM)



All effects by restoration measure
Dam removal
Hydromorph
Reforestation
Impact (imp:ref)
Recovery (rest:ref)
Restoration (rest:imp)
−3
−2
−1
0
1
2
Effect size (ln response ratio; ROM)

RESTOLINK: Preliminary results Decomposition

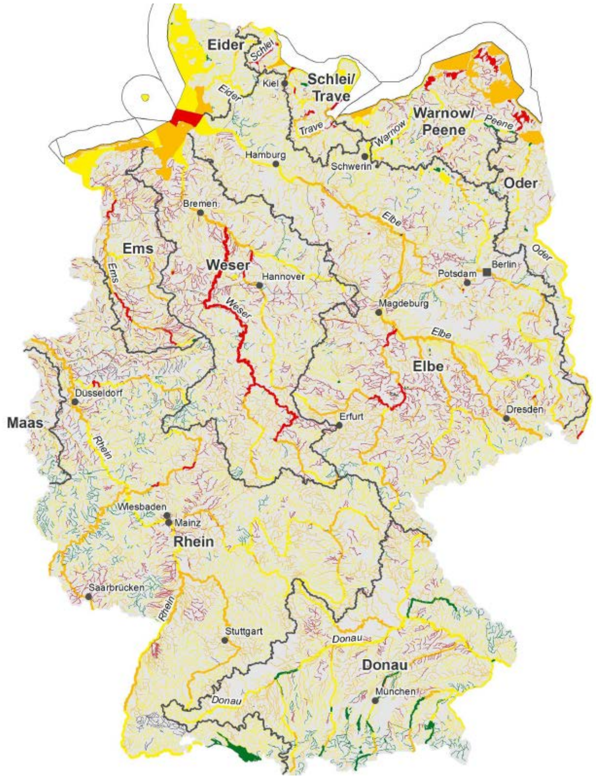
Cotton strip decomposition

CONCLUSIONS (so far)

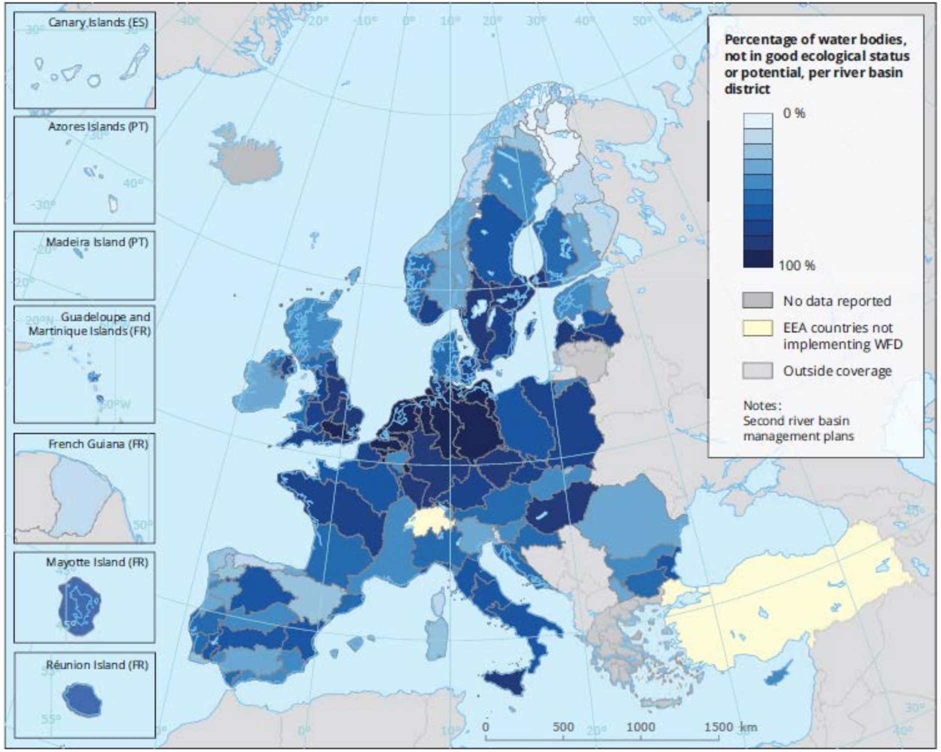
- ➔ Dam removal: Decomposition increased to rates of reference streams
- ➔ Hydromorphological restoration: No effect of restoration, but impacted streams did not have different rates from reference streams
- ➔ Reforestation decreased rates nearly to levels of reference streams

Quantifying restoration success across biomes by linking biodiversity, multifunctionality and hydromorphological heterogeneity - RESTOLINK

Ecological status of European waterbodies



UBA 2016, WISE WRRL Datenbank



EEA 2018, ECT 2020

Restoration as a means to return to reference status?

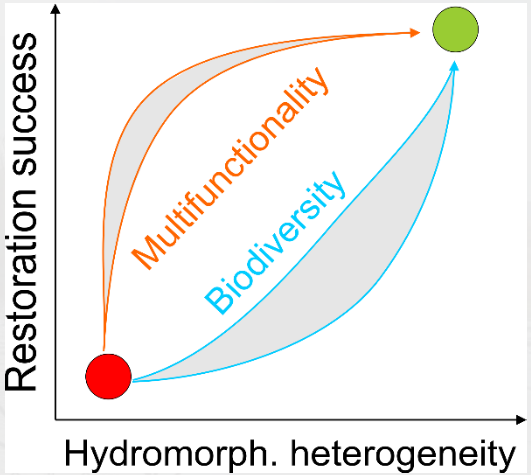
- "Ecological restoration is an intentional activity that initiates or accelerates the recovery of an ecosystem with respect to its health, integrity and sustainability."[1]
- "Land restoration is the acid test of our ecological understanding."[2]
- Most freshwater restoration measures are unsuccessful:
  - Inappropriate goals/restoration measures
  - Recolonization takes longer
  - Depauperate communities → no recolonization potential
  - Indicator problem

[1] SER International Primer on Ecological Restoration. www.ser.org
[2] Bradshaw D. (1987)

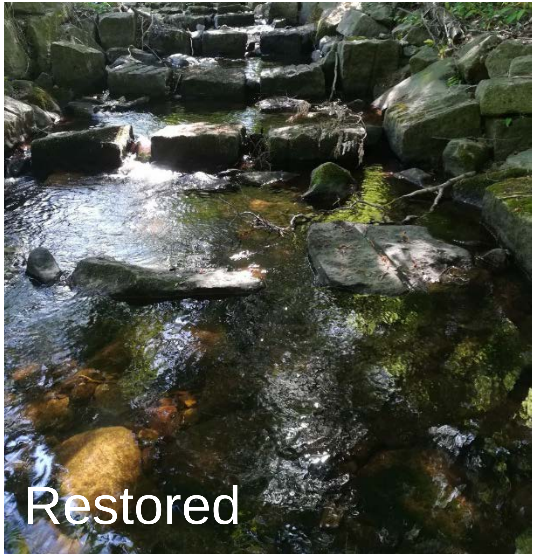
Current restoration targets

Overarching project aims

- Identify hydromorphological scales that need to be restored to recover microbial and macrobial biodiversity
- Decipher the role of biodiversity for ecosystem functioning
- Establish ecosystem (multi)functionality as a new indicator of restoration success



Approach



- 3 C-I-R triplets in Brazil, Germany, Spain and Sweden
- Sampling for hydrodynamics (3-d velocity, stream-bed roughness), biodiversity (micro-, macroorganisms) and function (OM degradation, nutrient uptake, whole-stream metabolism, GHG fluxes, food web)
- Stakeholder surveys
- Synthesis and meta-analysis of existing data

Can restoration compensate for the adverse effects of climate change on stream ecosystems?

Mario Brauns & Markus Hentschel

Contemporary restoration management

Restoring connectivity at the Ecker stream (Germany)

Contemporary restoration management

“Constructing a mean discharge channel facilitates fish migration towards their spawning habitats.”

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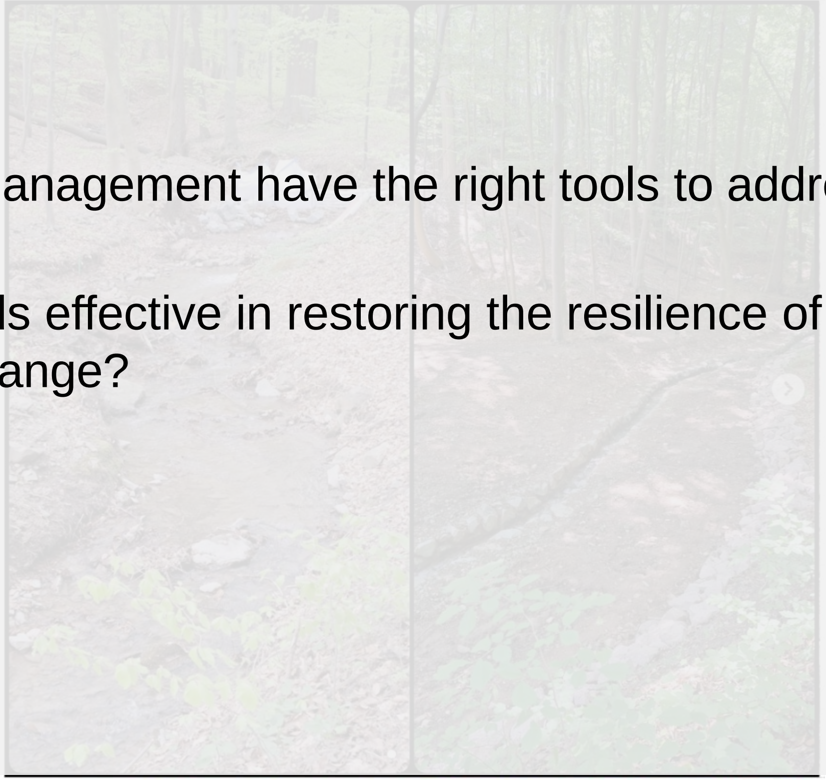
Contemporary restoration management

"Constructing a mean discharge channel facilitates fish migration towards their spawning habitats."



- Does restoration management have the right tools to address climate change?
- Are current methods effective in restoring the resilience of streams and rivers to climate change?

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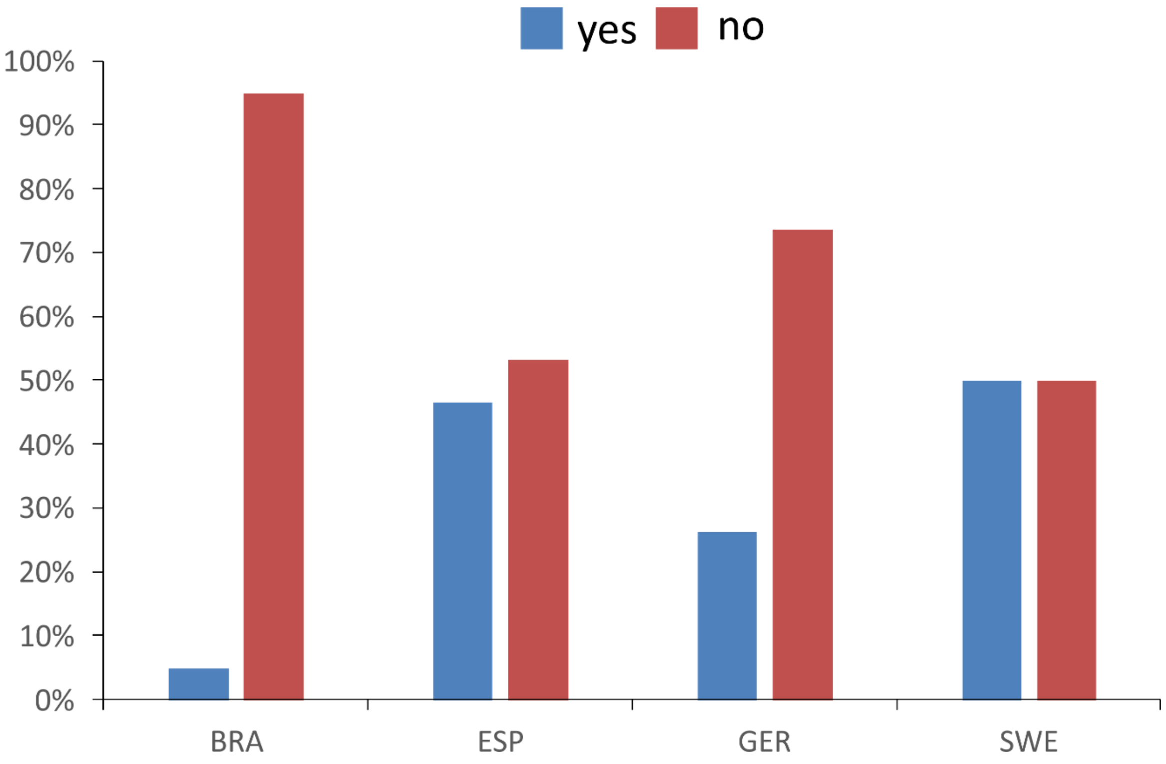
Practitioner survey

- Structured survey among Brazilian, Spanish, Swedish and German practitioners involved in restoration
- 107 practitioners filled out the survey: BRA: 31, ESP: 24, GER: 32, SWE: 20
- Do current biological reference conditions sufficiently account for climate change on restoration success?
- Do you feel confident in your ability to support or execute restoration projects focused on mitigating climate change?

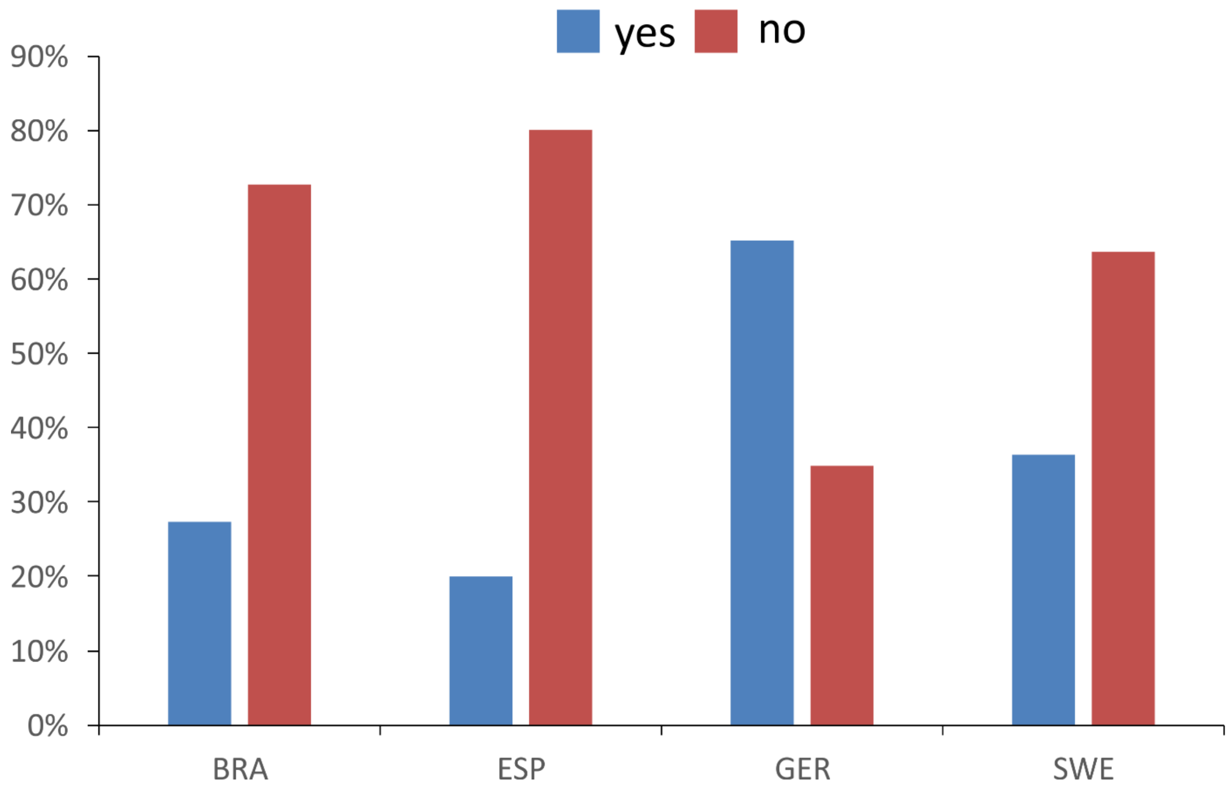
72% of practitioners: reference conditions ignore climate change

Do current biological reference conditions sufficiently account for climate change on restoration success?

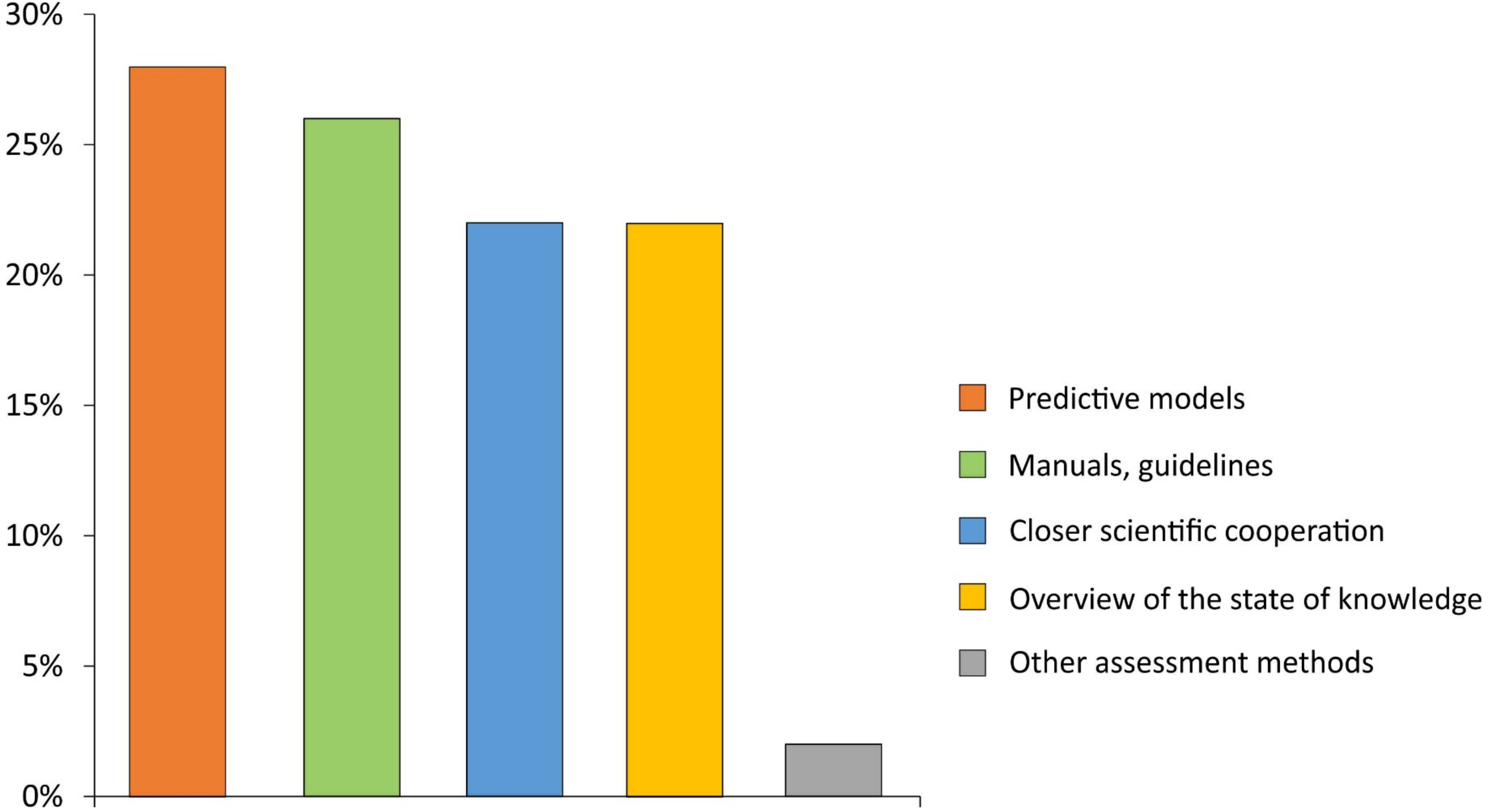


61% of practitioners: unable to implement CC-specific restoration

Do you feel confident in your ability to support or carry out restoration projects aimed at addressing climate change?



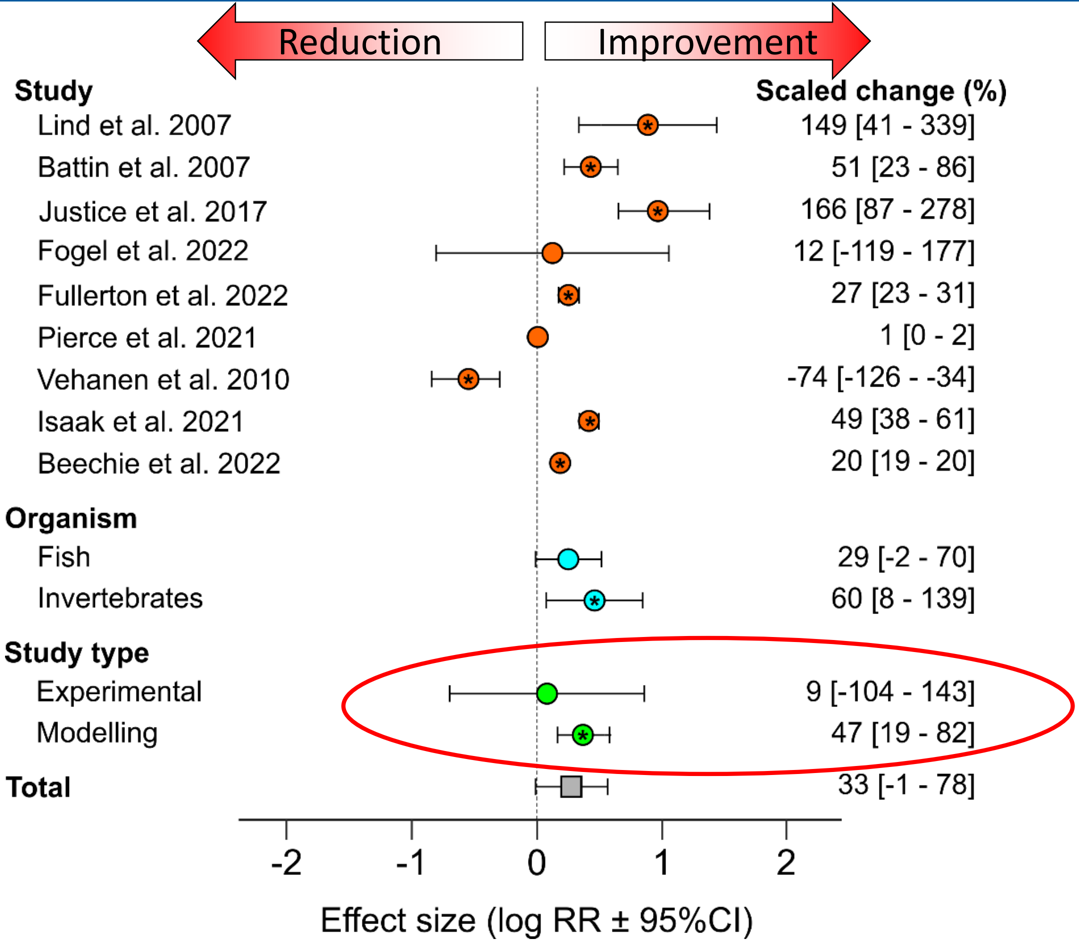
What do you need to implement CC-specific restoration projects?



Meta-Analyses

- Literature search in international, peer-reviewed publications (Web of Science) up to August 2024
- Search terms: Restoration OR Renaturation OR Revitalisation AND Stream OR River OR Running Waters AND “Climate change” OR drought OR flood OR “hydrological extremes” OR “environmental flows”
- 4,532 relevant studies identified, but only 44 met defined quality criteria
- 9 studies fulfilled selection criteria (restoration measure related to drought, before–after comparison, biological success indicators)
- Hydrological, morphological, or hydromorphological restoration measures, mostly combining multiple interventions
- Success indicators: benthic macroinvertebrates and fish
- Study types: experimental (field-based before–after comparisons) or modelling approaches (before–after comparisons with models, e.g. habitat suitability models)

Restoration measures to improve climate change resilience



Conclusions

- Restoration management is currently not prepared for climate change
- Call for manuals, guidelines, and models to predict restoration outcomes under different climate scenarios
- No empirical support, as current data availability is insufficient
- Significant difference between study types:
    - Modeling studies show biodiversity improvements
    - Experimental studies show no improvement or even biodiversity loss
- Urgent need for empirical or model-based studies, with before-after comparisons under hydrological extremes

UFZ HELMHOLTZ Zentrum für Umweltforschung

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