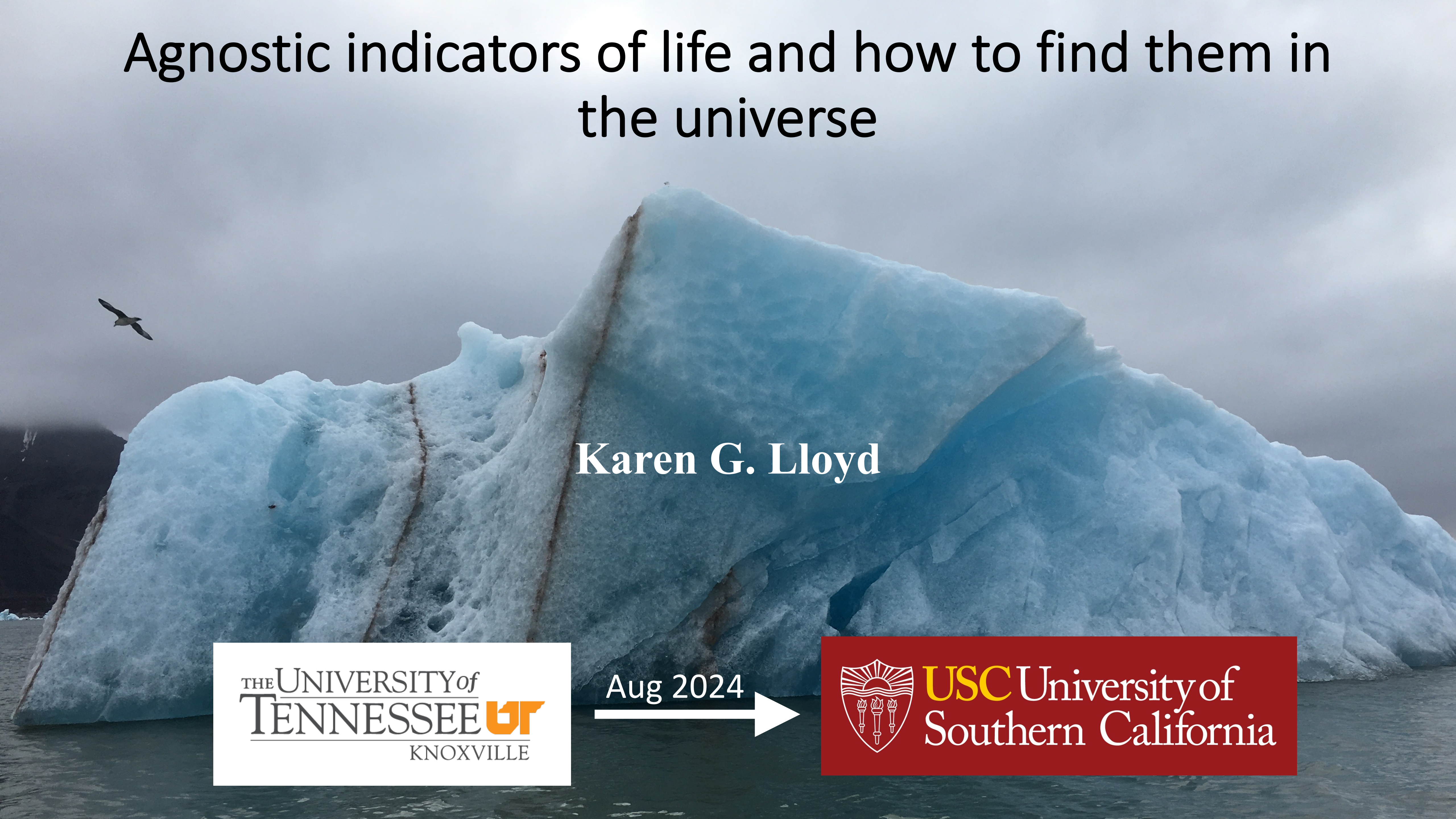
Agnostic indicators of life and how to find them in the universe



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What is an “agnostic” biosignature?

Evidence of life that is independent of any of the specifics of Earth life.

A universal indicator of life, that doesn’t presume that life has to have the same form as Earth life (e.g., DNA is not the only possible information molecule).

The problem is avoiding things that are specific to Earth life, but also avoiding being so general that you don’t know if you’ve got a living thing or not (for instance, a self-replicating crystal has a lot of the attributes of life).

There is a tradeoff between agnosticism and specificity.

Things we usually use for life-detection on Earth that are probably not universal

- DNA, RNA, proteins with 22-ish amino acids, lipids, metabolites, a specific set of metabolic reactions, chlorophyll and other photo-pigments
- Temperature and pressure limitations (Gold 1992 suggested silicon based life at depths where Earth is too hot to support stable carbon-carbon bonds).
- Time limitations – We assume that individuals die after 100 years, maximum, and that metabolism occurs over an observably fast timescale. We also assume an upper limit on speed, with reactions that occur too quickly being assumed to be abiotic. Life can't compete with an explosion, or can it?

Things that are agnostic, but probably not specific enough to be useful

- Catalyze (speed up) the destruction of potential energy.
- Create information systems to organize ultrastructures.
- Self-replicating.

THE ARCHITECTURE OF COMPLEXITY

HERBERT A. SIMON*

Professor of Administration, Carnegie Institute of Technology

(*Read April 26, 1962*)

A NUMBER of proposals have been advanced in recent years for the development of "general systems theory" which, abstracting from properties peculiar to physical, biological, or social systems, would be applicable to all of them.[1] We might well feel that, while the goal is laudable, systems of such diverse kinds could hardly be expected to have any nontrivial properties in common. Metaphor and analogy can be helpful, or they can be misleading. All depends on whether the similarities the metaphor captures are significant or superficial.

and to analyze adaptiveness in terms of the theory of selective information.[3] The ideas of feedback and information provide a frame of reference for viewing a wide range of situations, just as do the ideas of evolution, of relativism, of axiomatic method, and of operationalism.

In this paper I should like to report on some things we have been learning about particular kinds of complex systems encountered in the behavioral sciences. The developments I shall discuss arose in the context of specific phenomena, but the theoretical formulations themselves make

From Simons:

Life is a hierarchy of sub-populations. These sub-populations provide the necessary stable intermediate states that allow evolution to occur.

"We know today that both the biosphere as a whole, as well as its components, living or dead, exist in far-from-equilibrium conditions. In this context life, far from being outside the natural order, appears as the supreme expression of the self-organizing processes that occur." p. 175, "Order out of Chaos: Man's New Dialogue with Nature, Ilya Prigogene and Isabelle Stengers, 1984

In far-from equilibrium systems, stable structures can be maintained by constantly creating energy gradients, like eddies in a stream.

PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY B

Phil. Trans. R. Soc. B (2010) **365**, 1417–1427
doi:10.1098/rstb.2009.0272

Ecosystem biogeochemistry considered as a distributed metabolic network ordered by maximum entropy production

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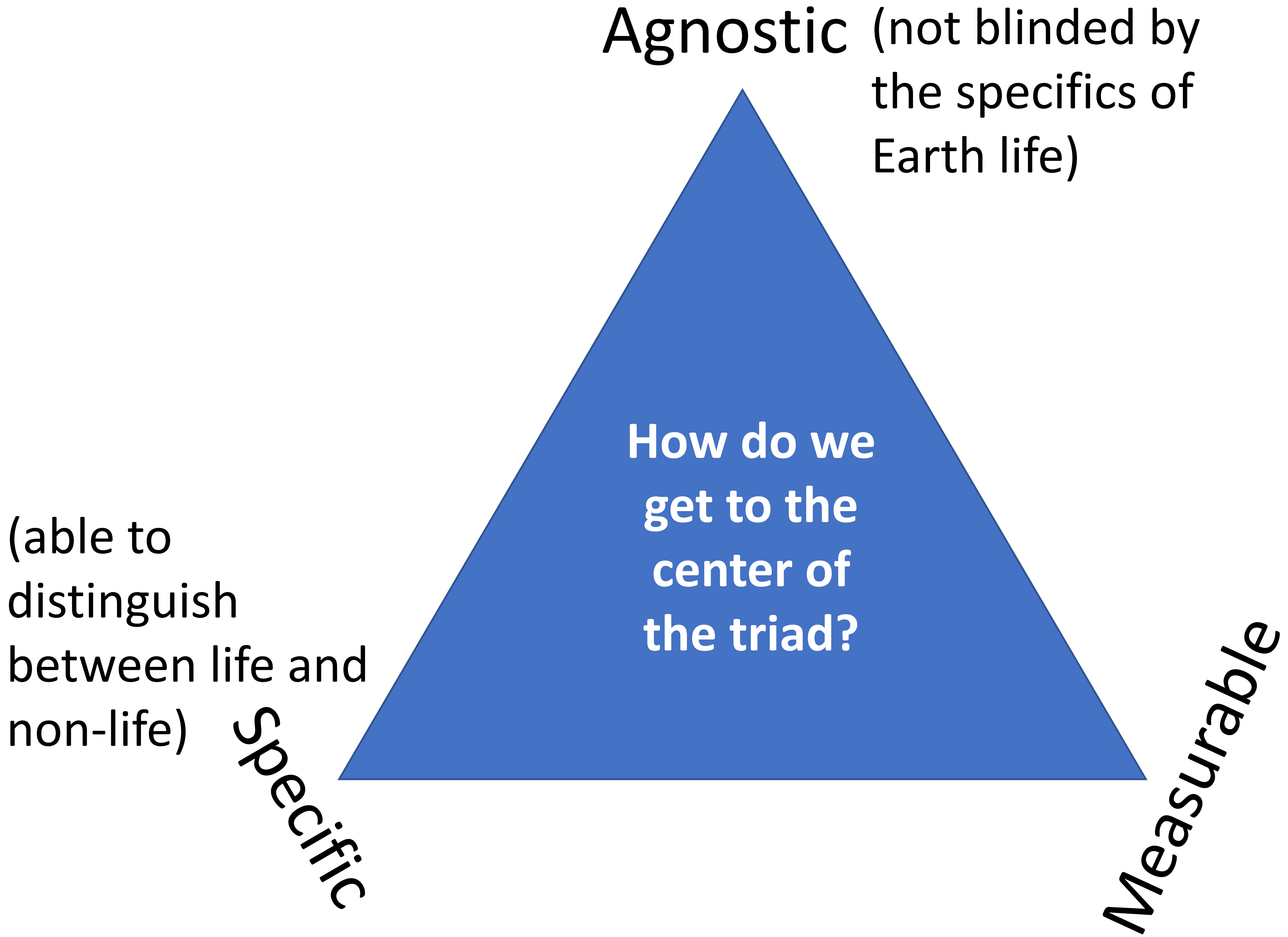
We examine the application of the maximum entropy production principle for describing ecosystem biogeochemistry. Since ecosystems can be functionally stable despite changes in species composition, we use a distributed metabolic network for describing biogeochemistry, which synthesizes generic biological structures that catalyse reaction pathways, but is otherwise organism independent. Allocation of biological structure and regulation of biogeochemical reactions is determined via solution of an optimal control problem in which entropy production is maximized. However, because synthesis of biological structures cannot occur if entropy production is maximized instantaneously, we propose that information stored within the metagenome allows biological systems to maximize entropy production when averaged over time. This differs from abiotic systems that maximize entropy production at a point in space–time, which we refer to as the steepest descent pathway. It is the spatio-temporal averaging that allows biological systems to outperform abiotic processes in entropy production, at least in many situations. A simulation of a methanotrophic system is used to demonstrate the approach. We conclude with a brief discussion on the implications of viewing ecosystems as self-organizing molecular machines that function to maximize entropy production at the ecosystem level of organization.

Non-equilibrium thermodynamics give us features that are agnostic and specific, but hard to connect to things we can actually measure

Look for patterns in hierarchical, information-rich systems that maintain themselves far from equilibrium and maximize entropic production by extending it over increasingly longer timescales.

How do you measure this with a gas chromatograph?


Agnostic (not blinded by the specifics of Earth life)
How do we get to the center of the triad?
(able to distinguish between life and non-life)
Specific
Measurable

Goal: To highlight the nutrients and potential metabolic processes of subsurface microbiology

What are the nutrients that life needs?

Molecules that can react and microbes conserve **energy** from them.

Molecules that contribute **building material** for life.

--Pairs of compounds or elements that are good at giving up or accepting an electron (respiration)

-Most transition metals, H_2, CO_2, CO, S, C, N, As, Se, halogens.

-Any reaction that is exergonic, but slow.

-Easiest pair – H_2 and CO_2 for methanogenesis and acetogenesis.

--Single compounds that can be split into a more oxidized molecule and a more reduced molecule

-Simple organic carbon molecules (fermentation)

-Stable inorganic molecules of intermediate oxidation state (disproportionation)

--Two molecules of different oxidation states combining to form a single molecule (comproportionation). NH4+ and NO_2^-, H_2S and SO_4^{2-}

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methanogenesis and ...

Ranges from -10 kJ/mol (painfully low energy) to minus thousands of kJ/mol (enough to play tennis and laugh at dumb jokes)

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...tion states combining ...portionation). NH4+

Almost always pretty low energy.

The low energy processes can produce vast amounts of product (because they need to compensate for low energy with fast turnover.

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Molecules that contribute **building material** for life.

--CHNOPS plus metals common in enzyme cofactors (Fe, Ni, S, Co, Cu, Mg, W, Zn, V, Se, Mn)
--Often in higher abundance in the subsurface.

What are the sources for subsurface nutrients on Earth?

Stuff that falls in from the surface:
--Plant matter, including anything from primary or secondary production from photosynthetic life
--Ancient reservoirs of dead plant matter
--Energetic nutrients are plentiful (because, the sun), but building block nutrients can be limiting.

Example ecosystems:
--Marine sediments (a massive ecosystem on Earth)
--Subsurface aquifers with heavy recharge
--Coal, petroleum, methane deposits.

Nutrients sourced from the subsurface:
--Serpentinization – water-rock reactions and their downstream reactions that generate heat, mineral fracturing, H_2, Fe(III), CO_2, CH_4, and CO.
--Other hot water-rock reactions.
--Degassing of mantle and downgoing slab produces H_2, CO_2, methane, ammonium
--Radiolysis of water produces H_2 and sometimes CO_2.
--Abiotic thermal synthesis of organic carbon.
--We have evidence of chemolithoautotrophy-based ecosystems, but no known ancient reservoirs of biomass from these processes

Example ecosystems:
--Hydrothermal vents
--Natural springs
--Deep, ancient aquifers

These types of environments often produce fluids that pop up to the surface, for ease of sampling.

How can we detect subsurface life, agnostically?

- Come up with new measurements to make.
- Find innovative ways to measure data-types that are already possible to obtain. That is, work within existing datastreams to find something more fundamental about life detection.

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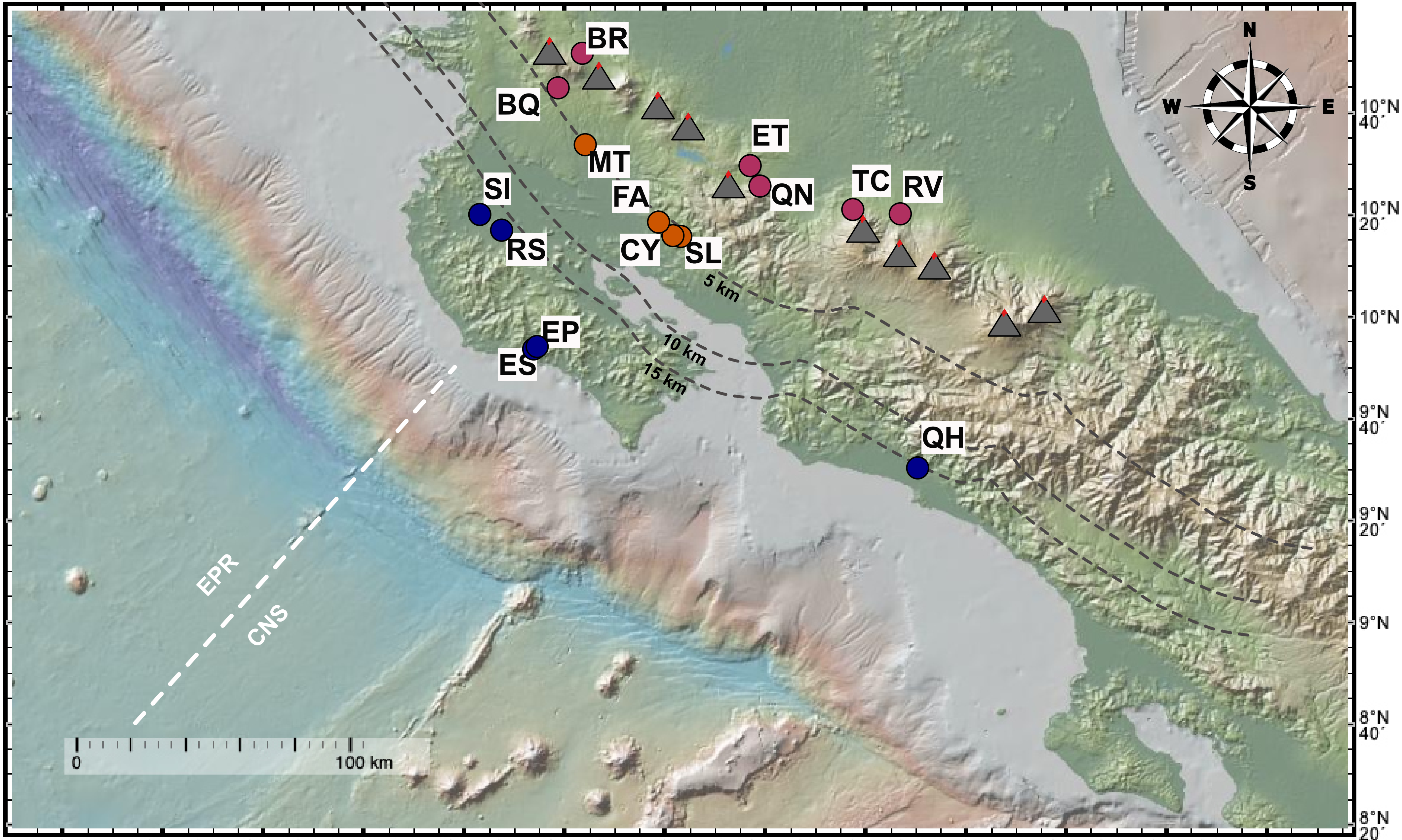
Analogies from my own research and those of others, to help stimulate discussion

- **Co-correlation networks**: Detecting life in the subsurface biosphere and their metabolisms by correlating DNA, RNA, and metabolites across many samples.
    1. Co-correlating 16S rRNA gene reads across Costa Rica springs to detect subsurface life.
    2. Co-correlating metagenomic reads across Costa Rica springs to put together metabolic pathways.
- **Machine learning techniques**:
    1. Correlation networks on steroids.

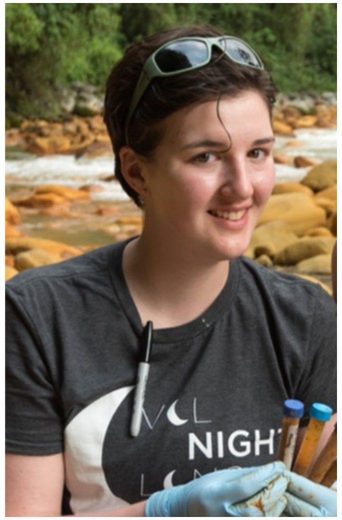


Rogers et al., 2023, ISME J

Mayuko Nakagawa, ELSI, Japan

Mustafa Yucel, Middle East Technical U., Turkey

Current and former members of my lab group:



Kate Fullerton

Joy Buongiorno,

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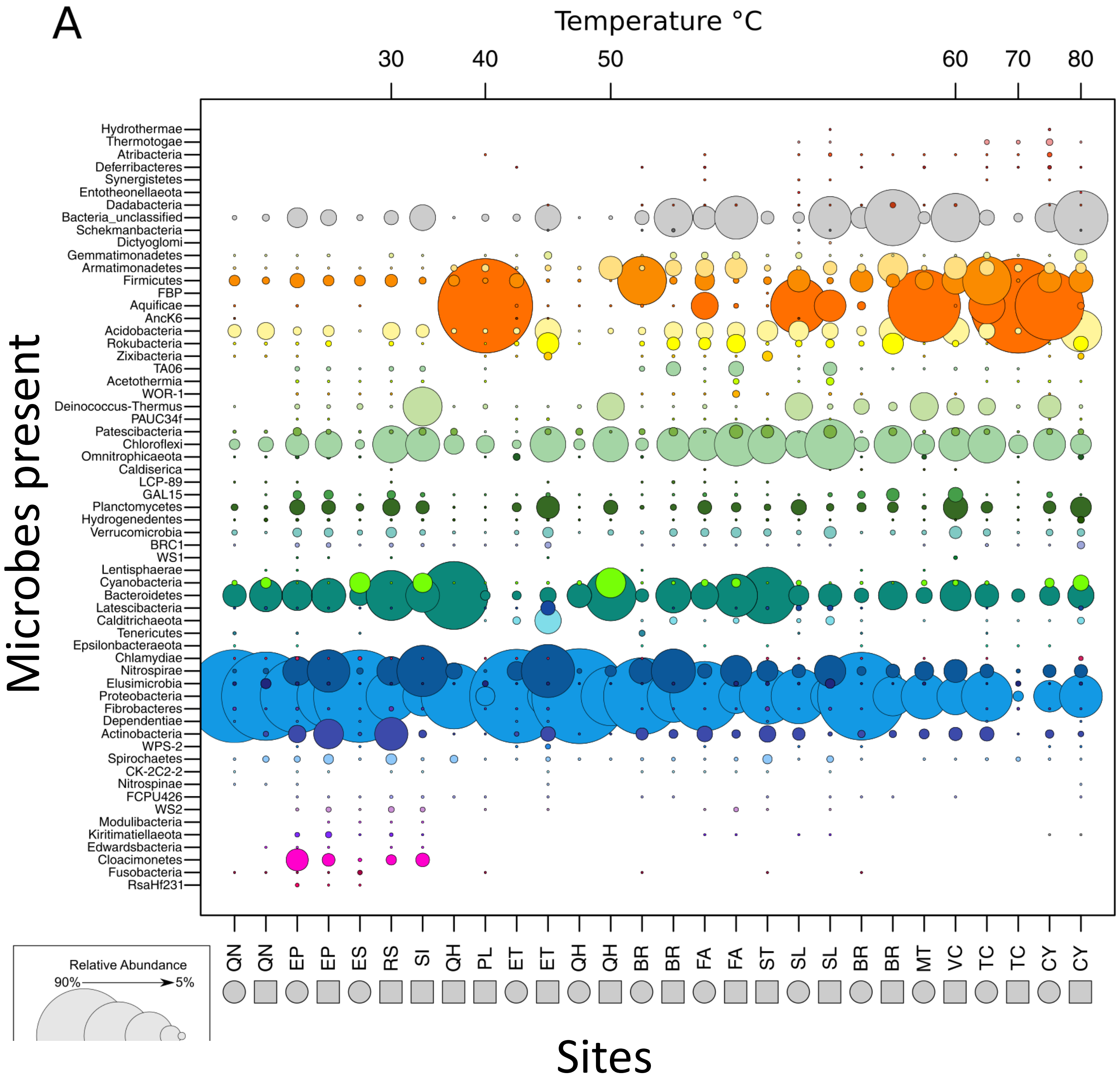
Peter Barry, WHOI
Donato Giovannelli, U. Naples
Maarten de Moor, National U. of Costa Rica

1. Correlations to detect subsurface life

When you measure fluids springing out of the subsurface, what microbes were flushed out of the subsurface, and what got mixed in from recent rainwater?

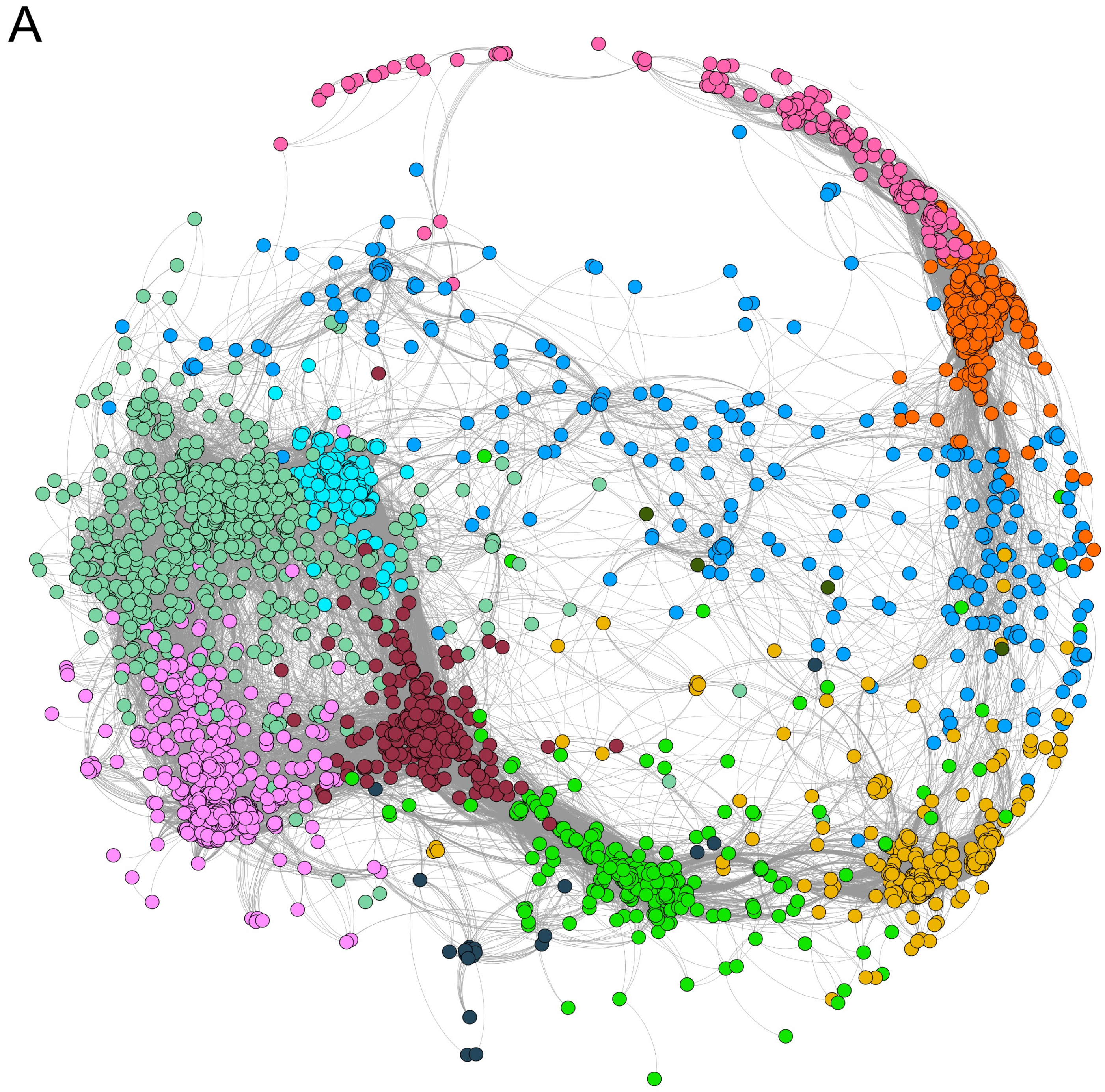


This is a lot of microbes.

How do we figure out how each of them is interacting with the deep tectonic processes?

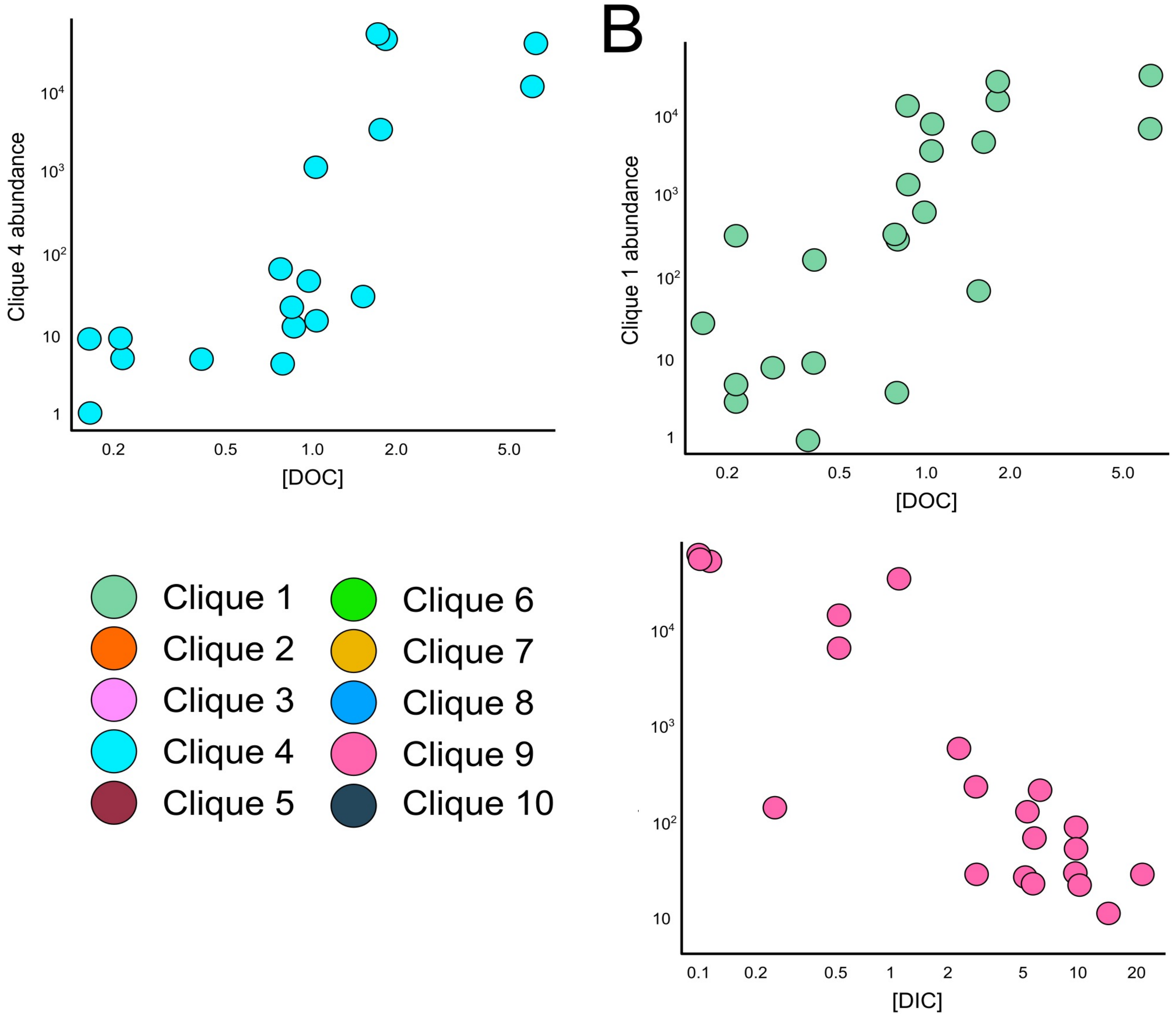
Fullerton et al., 2021 Nat. Geosci.

Reduce the complexity of the problem. Divide microbes into groups that correlate in abundance and see how they relate to geochemistry.



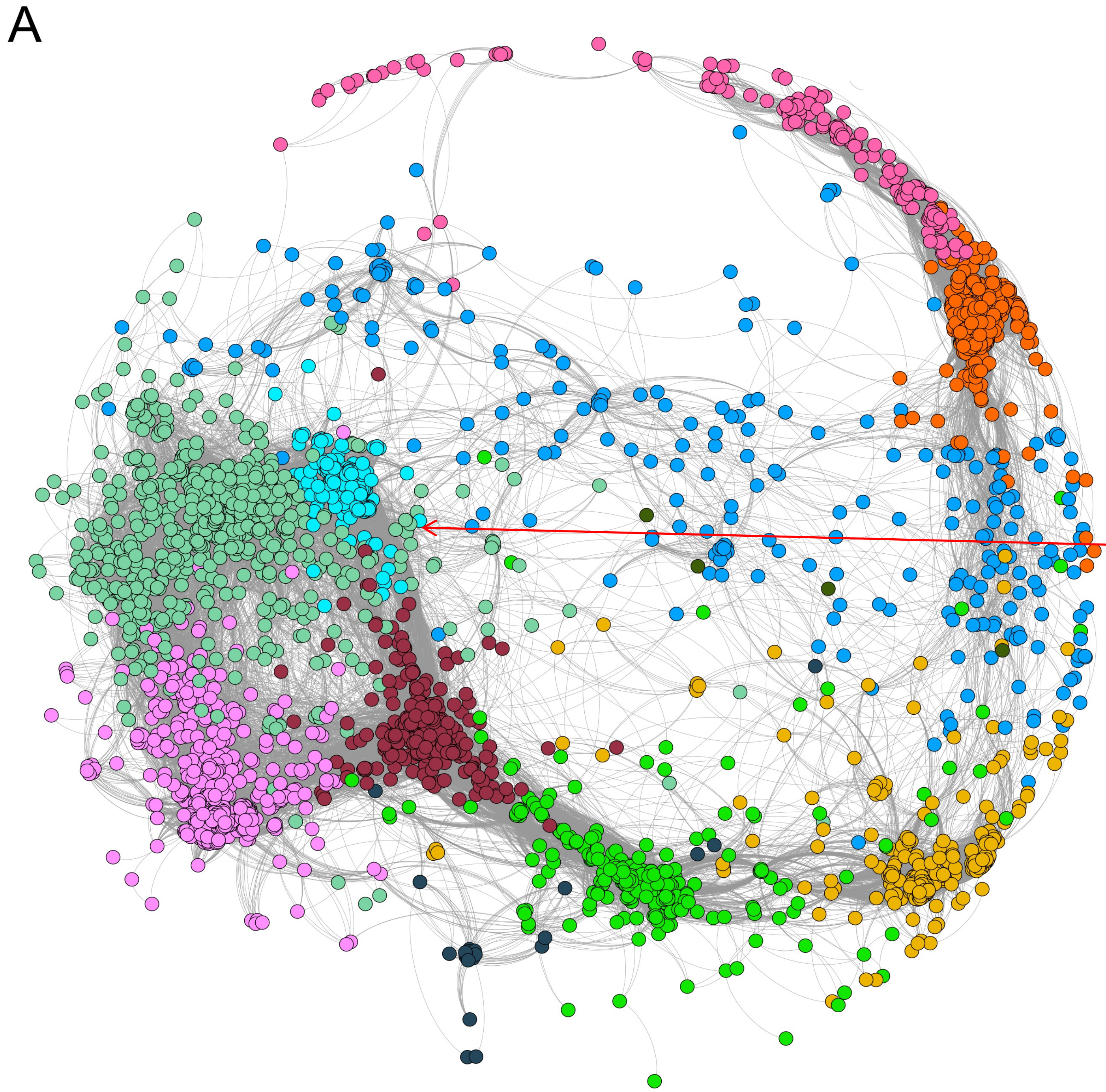
Network analysis: Each dot is a different 16S sequence. Colors represent “cliques” of microbes that hang out together.

Fullerton et al., 2021 Nat. Geosci.



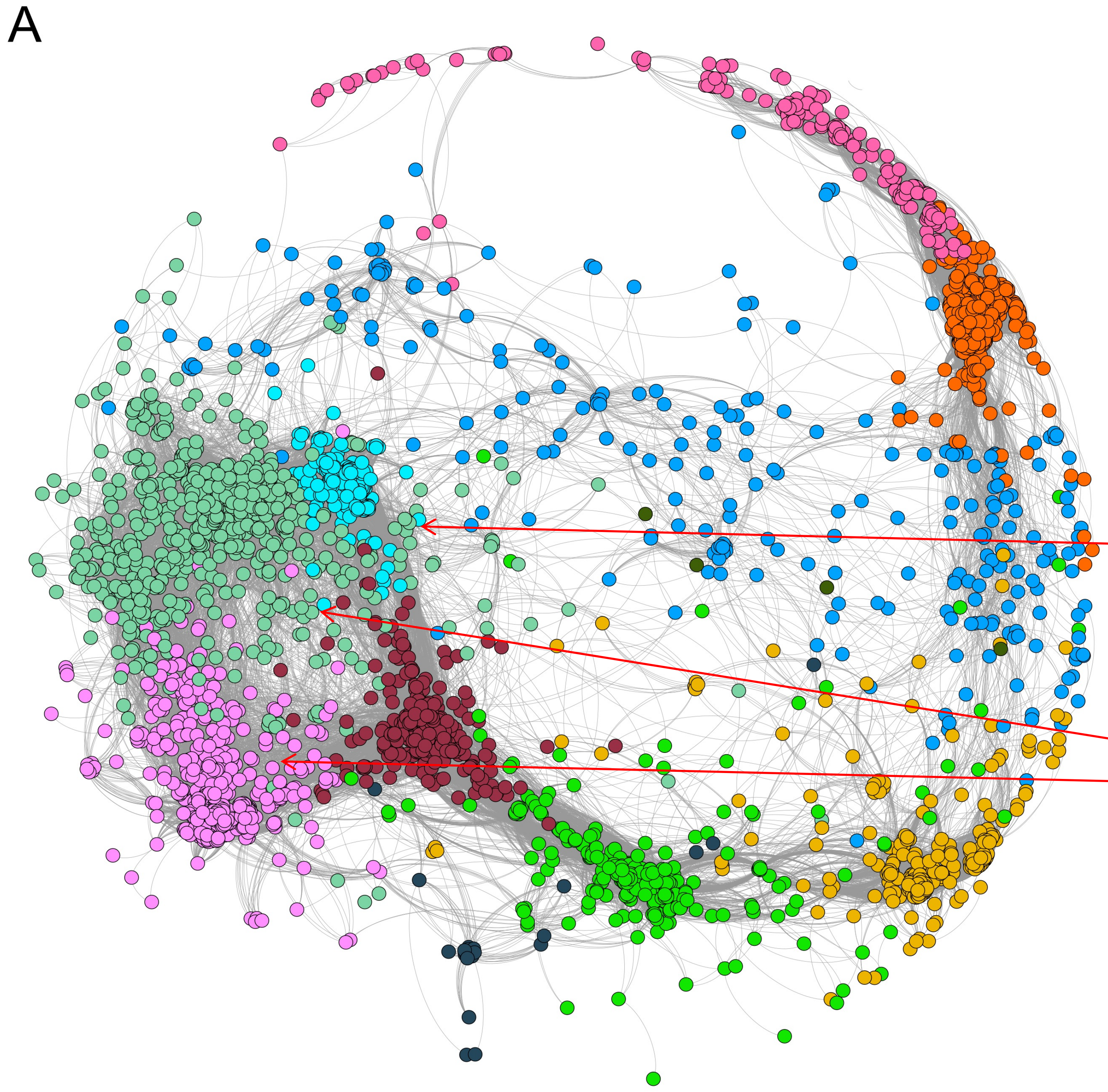
The biggest cliques correlated best with the concentration of DIC and DOC, and they were comprised of known autotrophs.

Fullerton et al., 2021 Nat. Geosci.



These are the main primary producers where the plate is deep (100 km deep), and they use iron and sulfur for chemosynthesis.

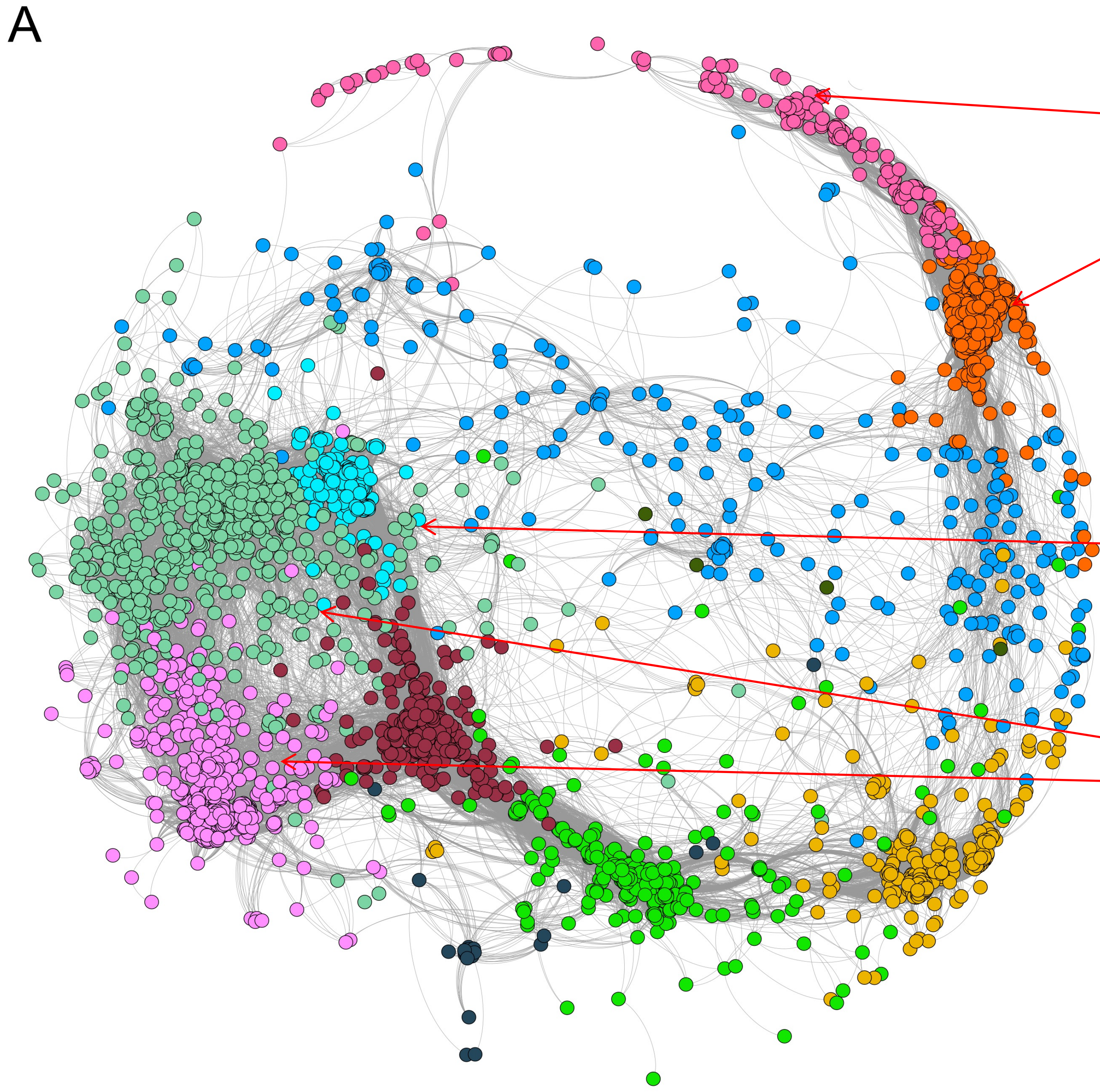
Fullerton et al., 2021 Nat. Geosci.



These are the main primary producers where the plate is deep (100 km deep), and they use iron and sulfur for chemosynthesis.

These are the heterotrophs that eat what the primary producers make.

Fullerton et al., 2021 Nat. Geosci.



These are primary producers when the tectonic plate is shallow (only 20 km deep), and they use sulfur for chemosynthesis. They are good at using scarce carbon resources.

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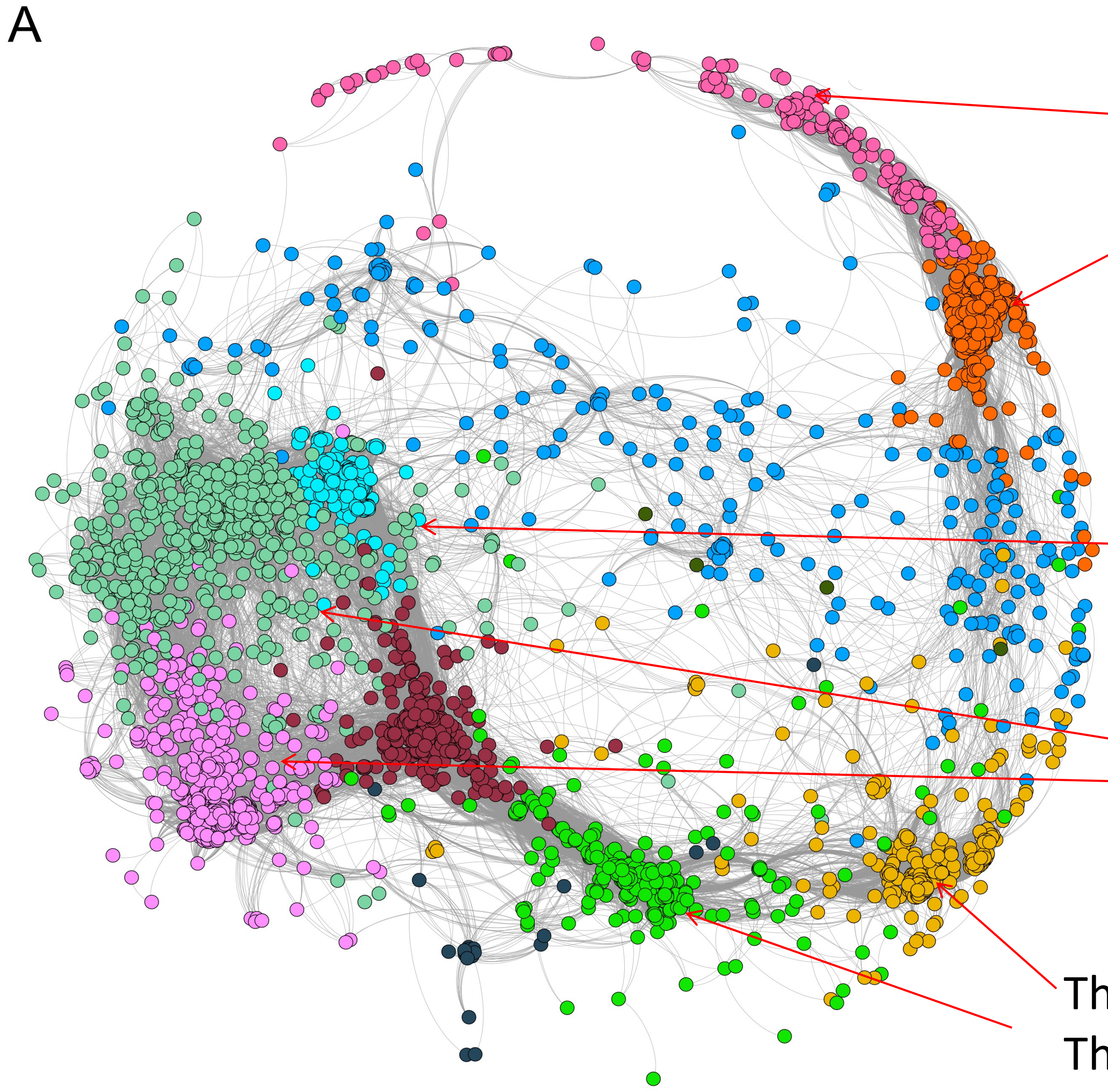

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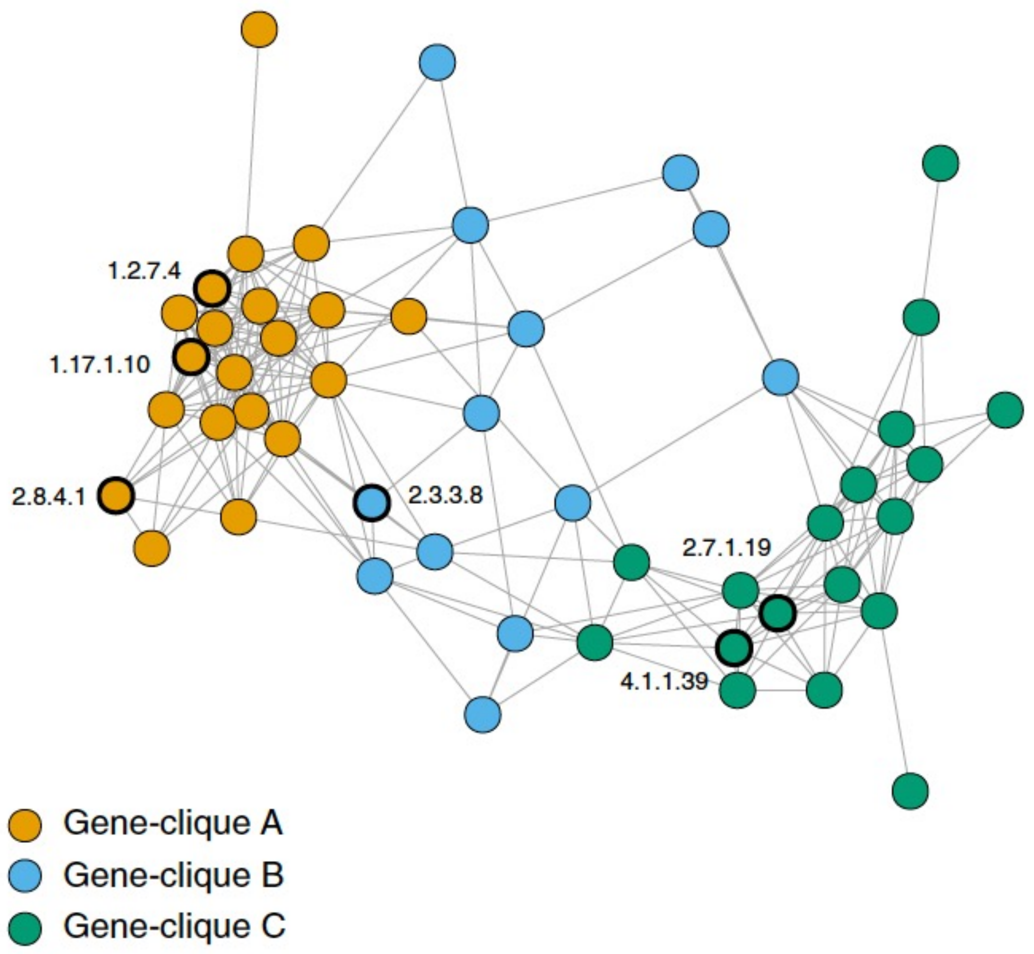
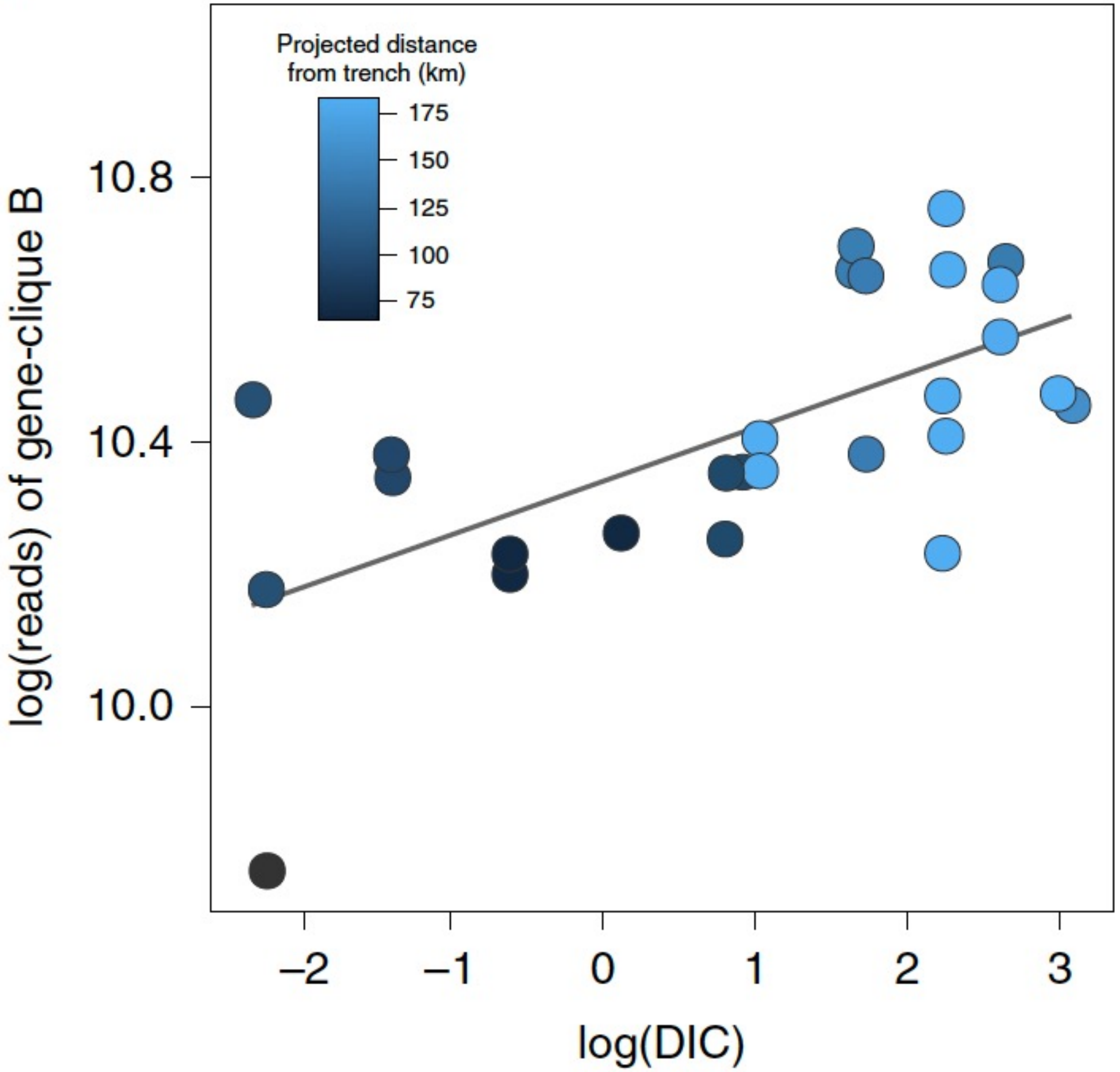
These just got washed in from soils. They’re probably really unhappy.

Things we found through correlations

1. Distribution of microbes through 16S rRNA showed us which came from subsurface vs. surrounding soils.

2. Correlations to detect metabolic pathways (without presuming the pathway *a priori*)





Things we found through correlations

1. Distribution of microbes through 16S rRNA showed us which came from subsurface vs. surrounding soils.
2. Distribution of functional genes across natural springs showed which ones work together in a metabolic pathway.

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How do you measure this with a gas chromatograph?

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How do you measure this with a gas chromatograph?

You might be able to measure this with ANYTHING, as long as you're looking for patterns in the right way.

Thank you!

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