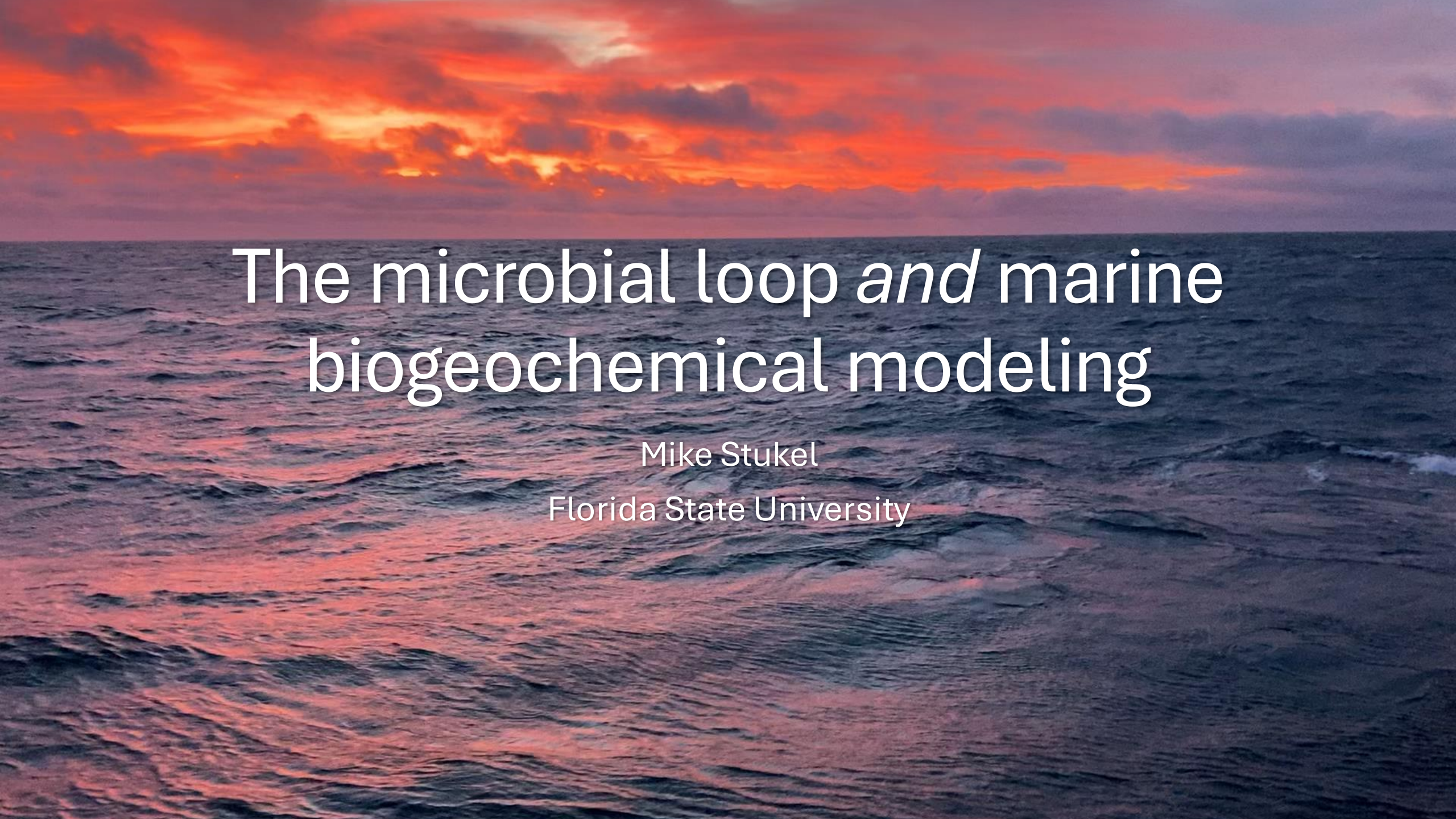


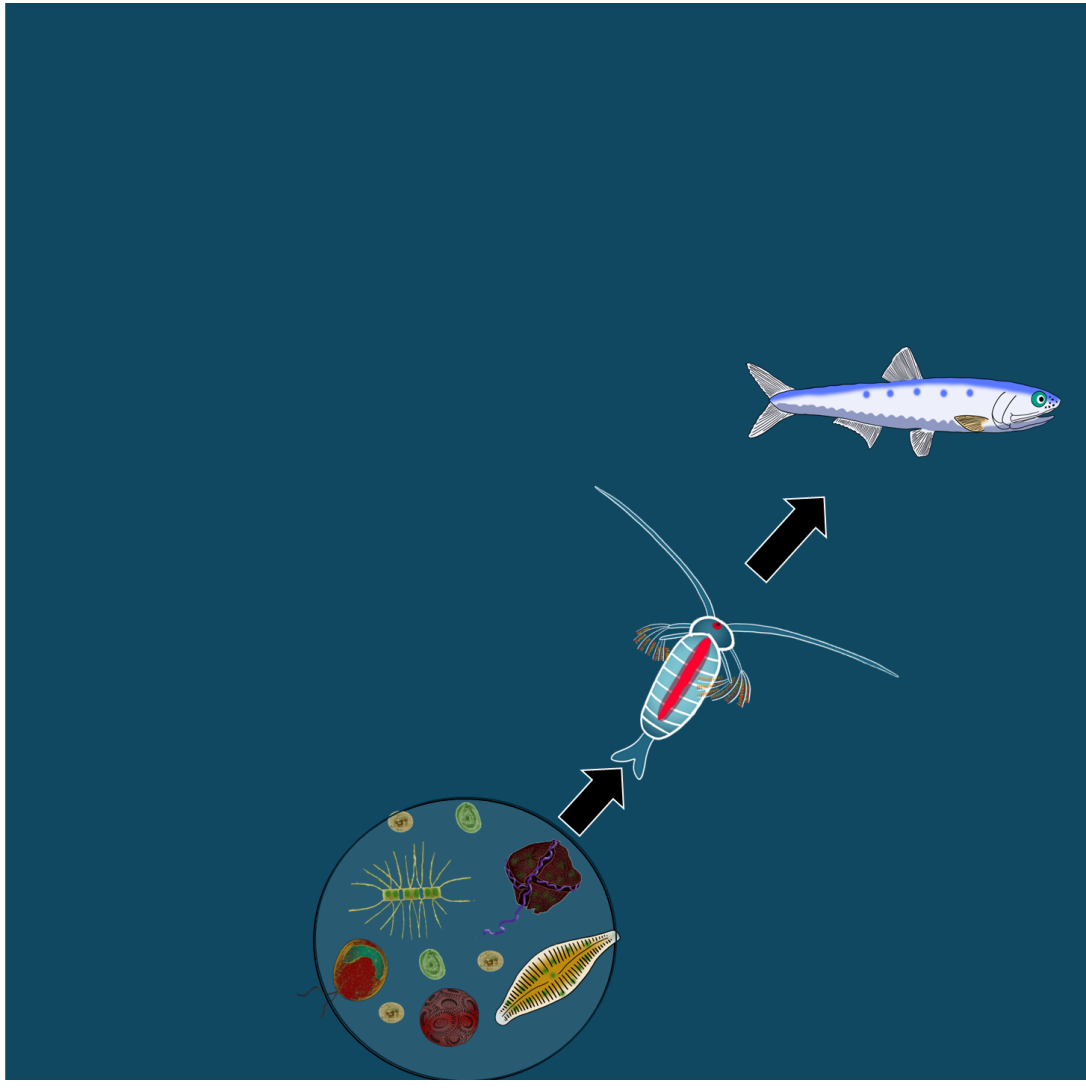
The microbial loop *and* marine biogeochemical modeling

Mike Stukel

Florida State University

Evolution of the microbial loop paradigm

- 1980s – Bacteria are abundant & microbial loop exists
- 1990s – Microbial loop is crucial for nutrient remineralization
- 2000s – Protists are dominant grazers of phytoplankton
- 2010s – Viruses enhance microbial diversity
- 2020s…
  - Species-level interactions matter
  - Protistan grazers also promote diversity
  - Microbial “hotspots” are common and diverse
  - Mixotrophy is a common nutritional strategy



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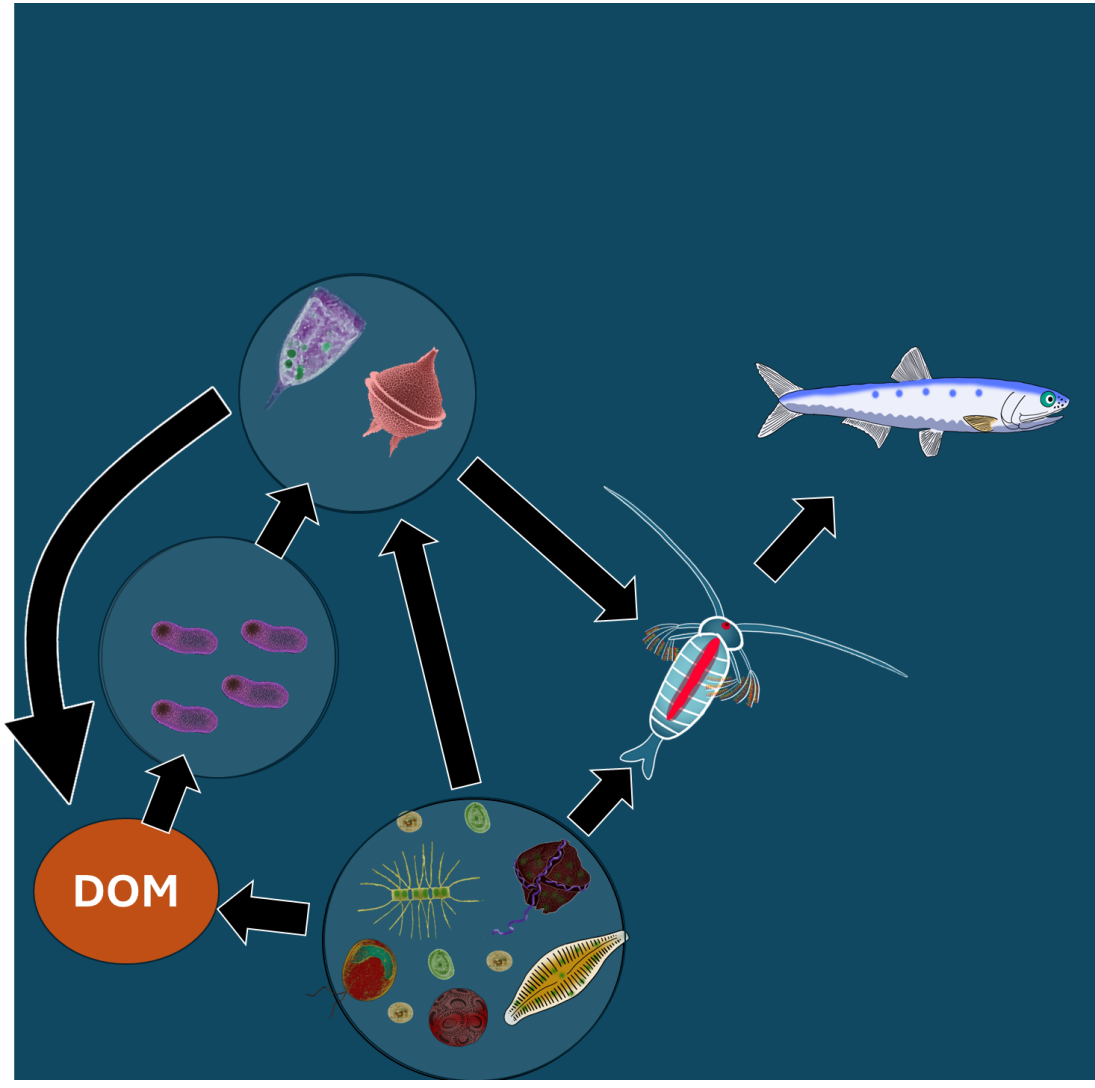

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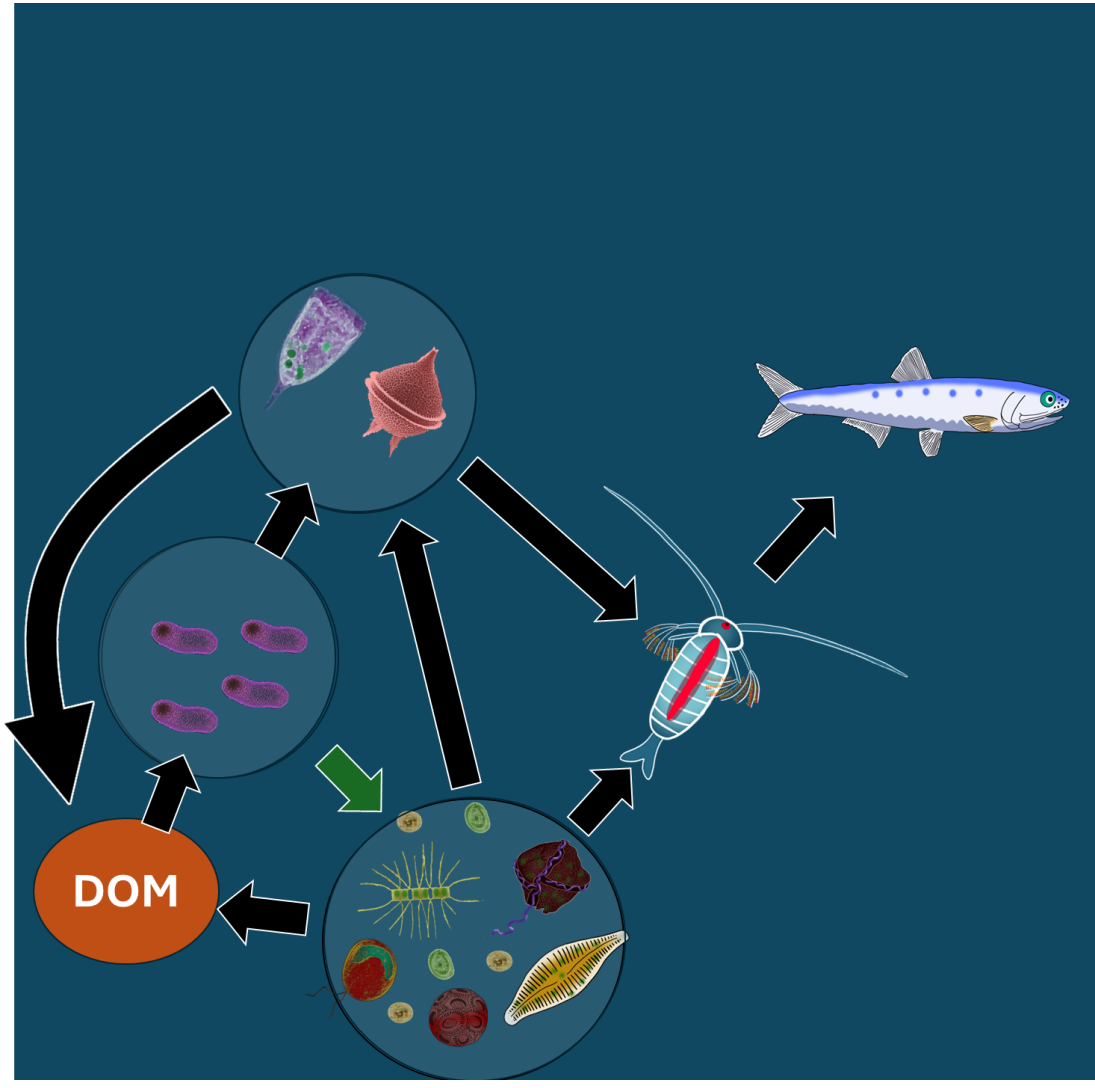

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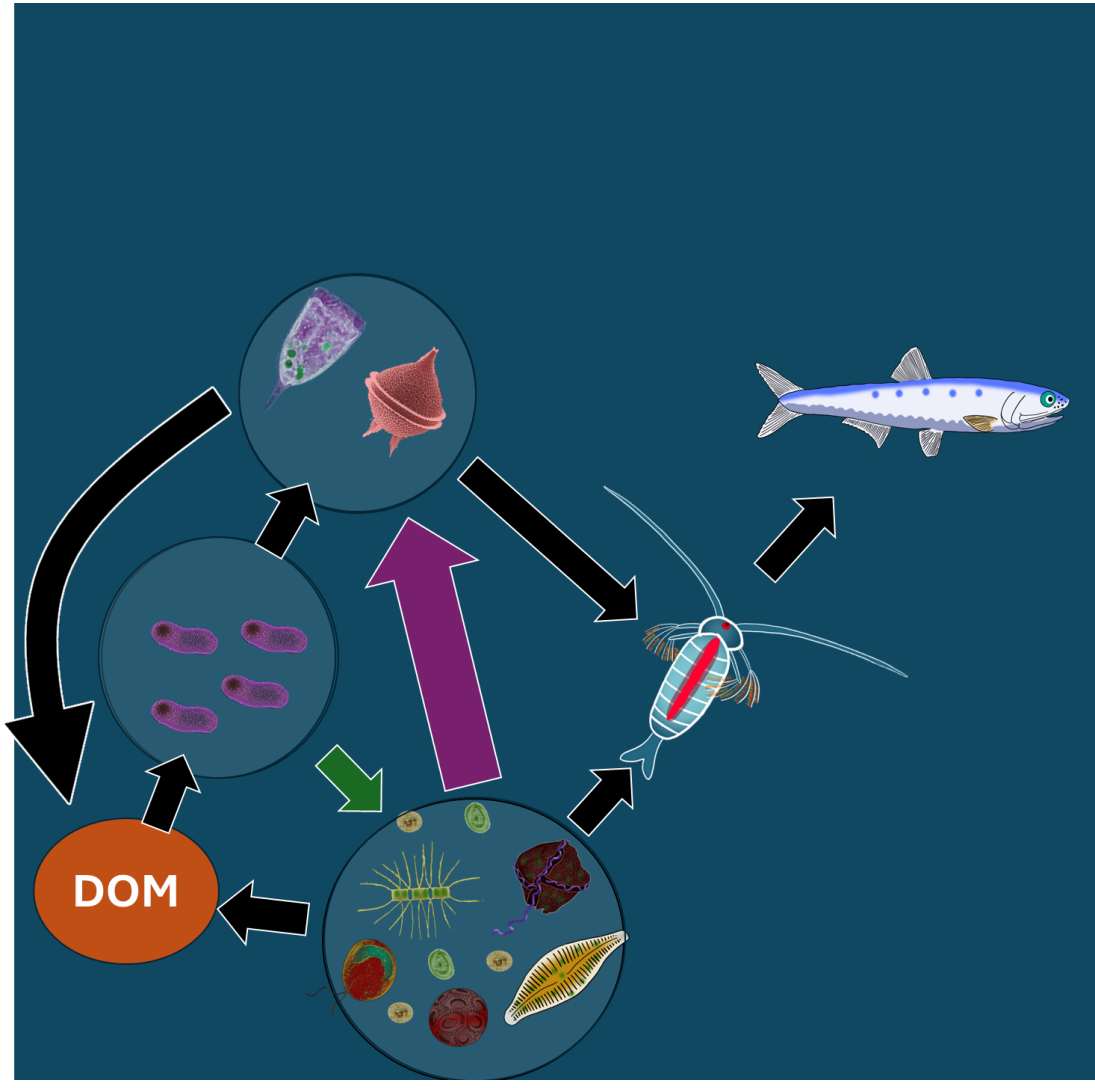

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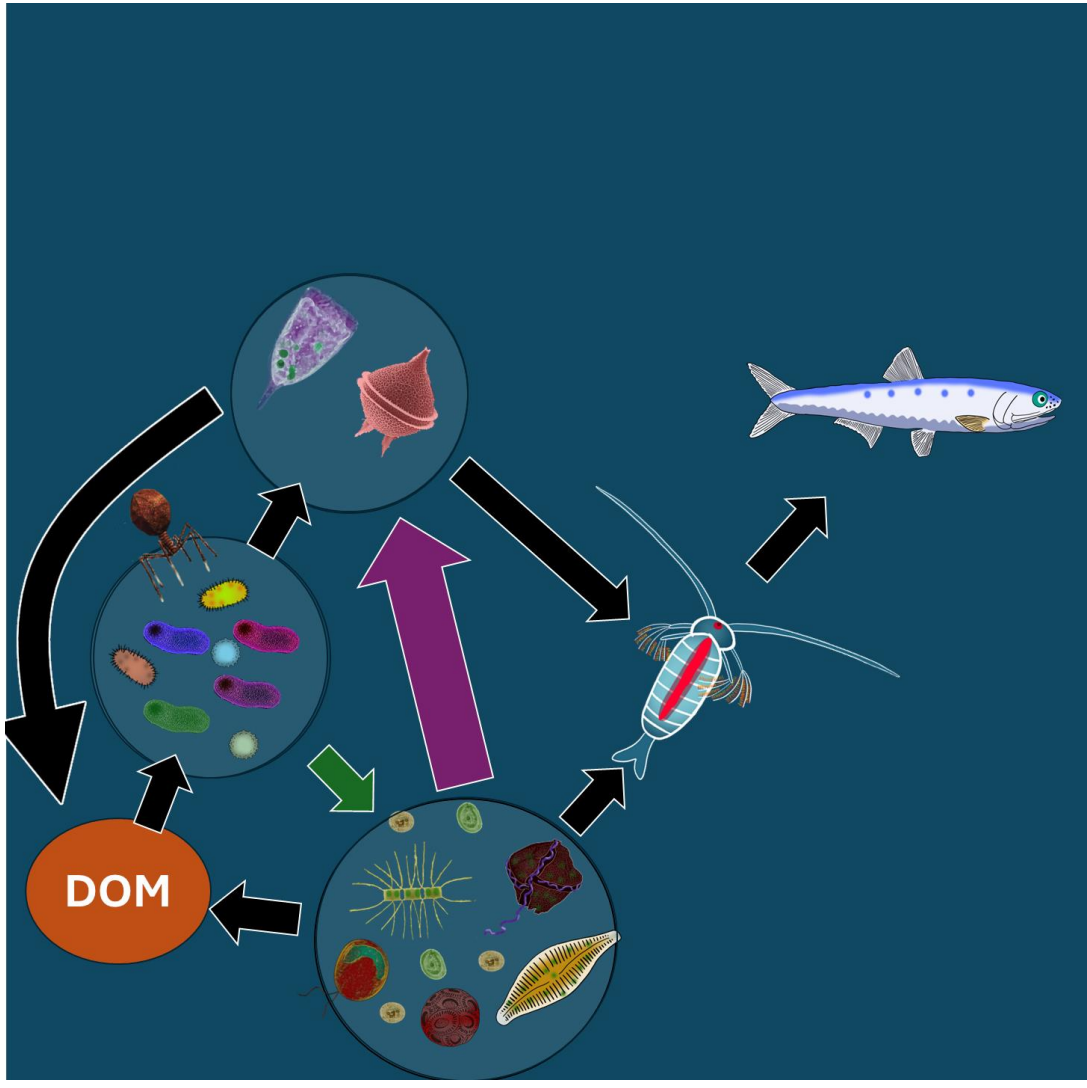

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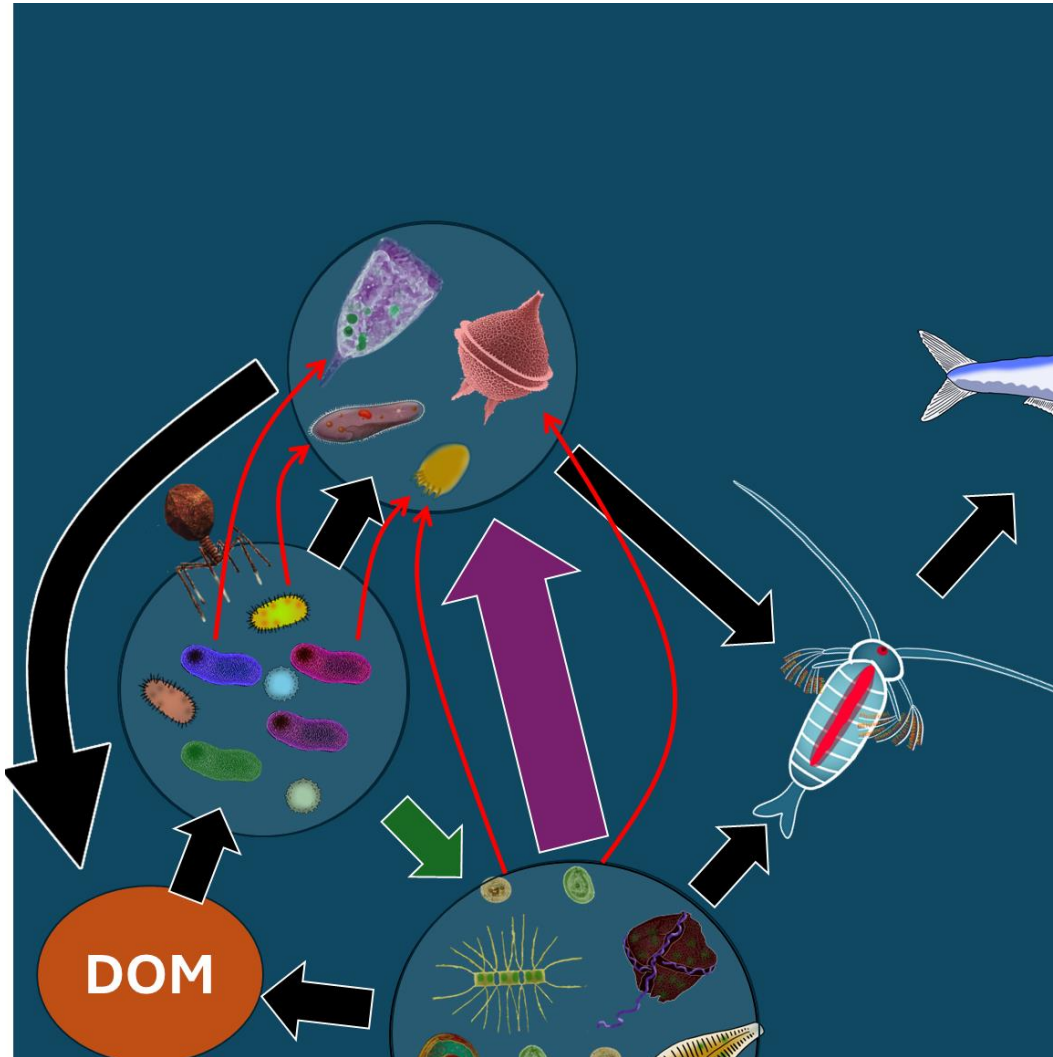

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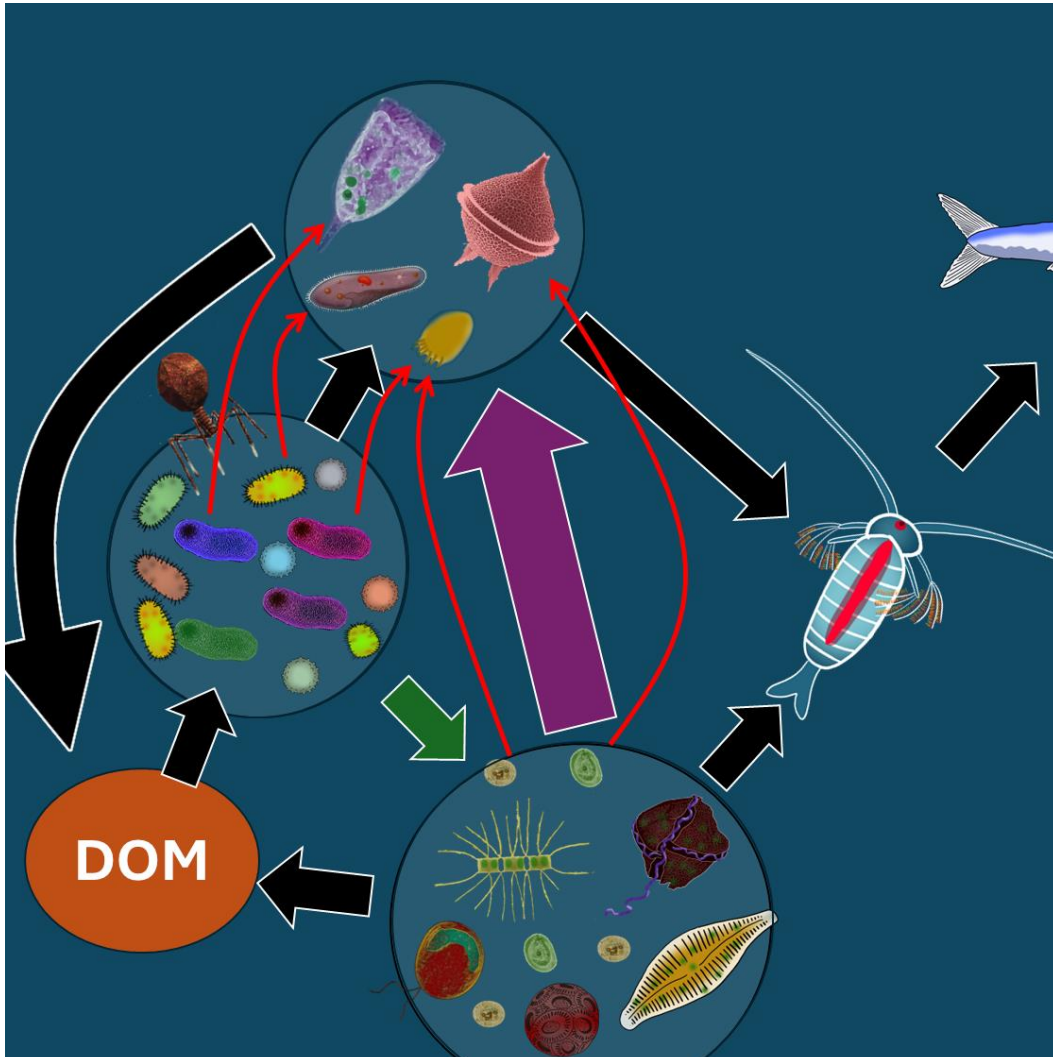

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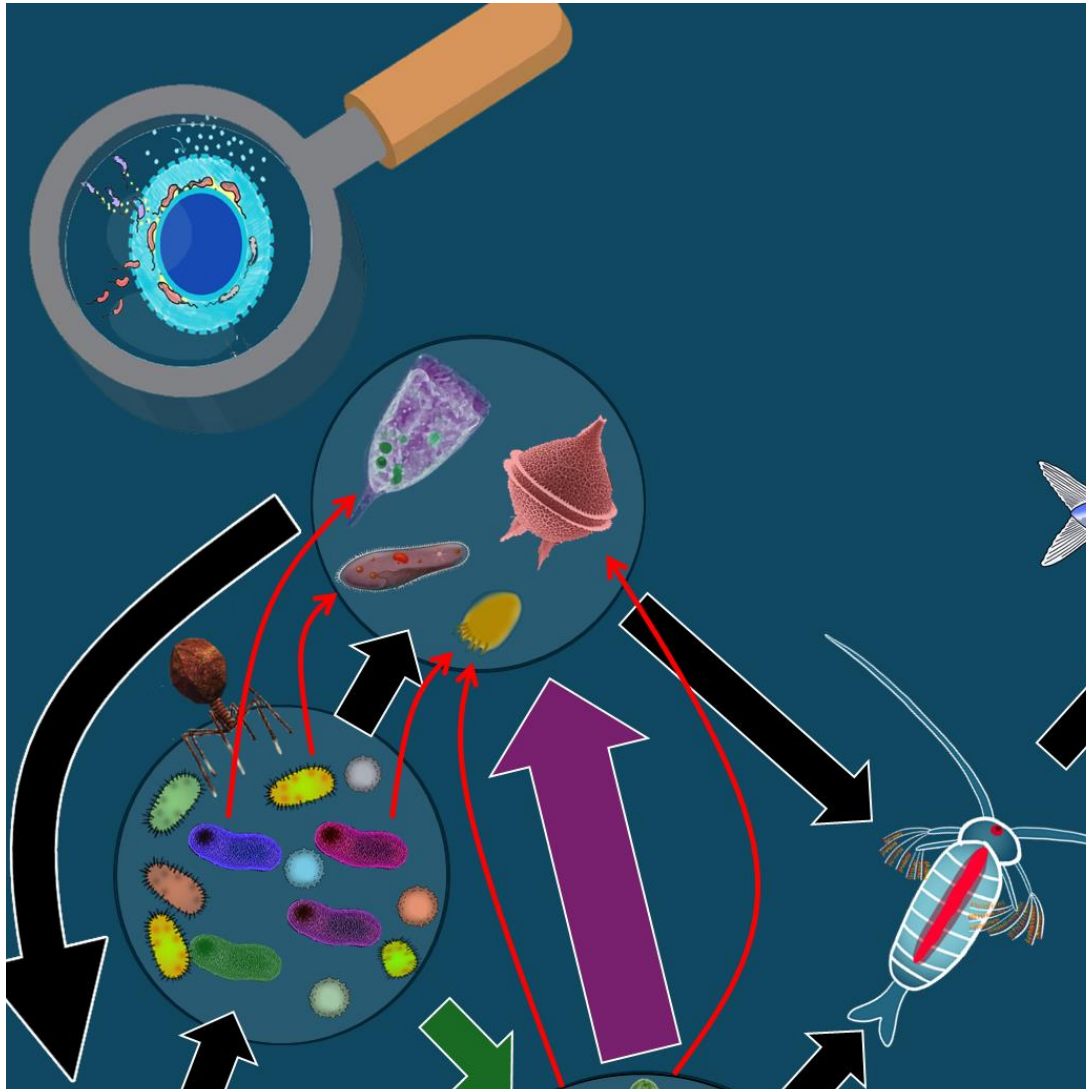

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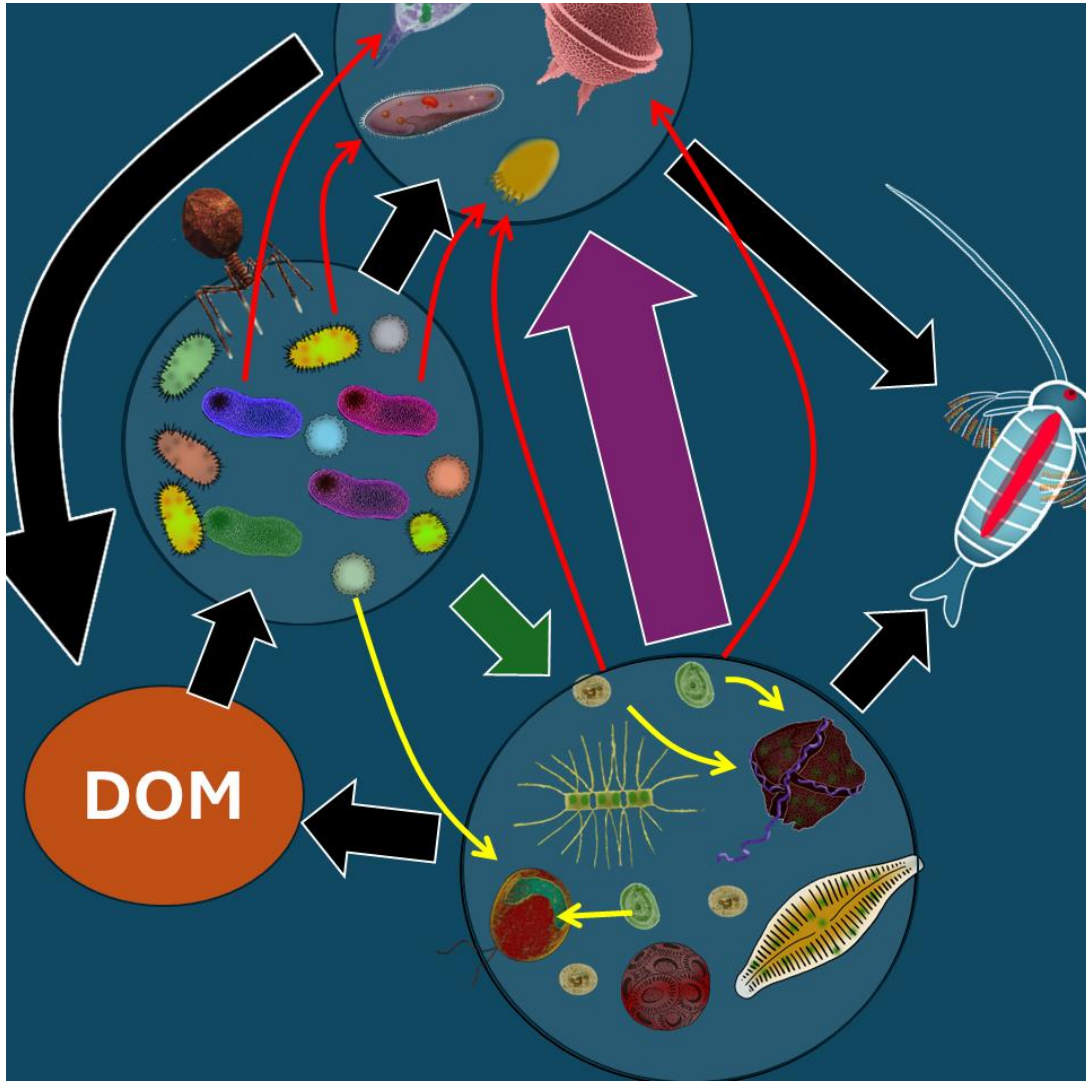
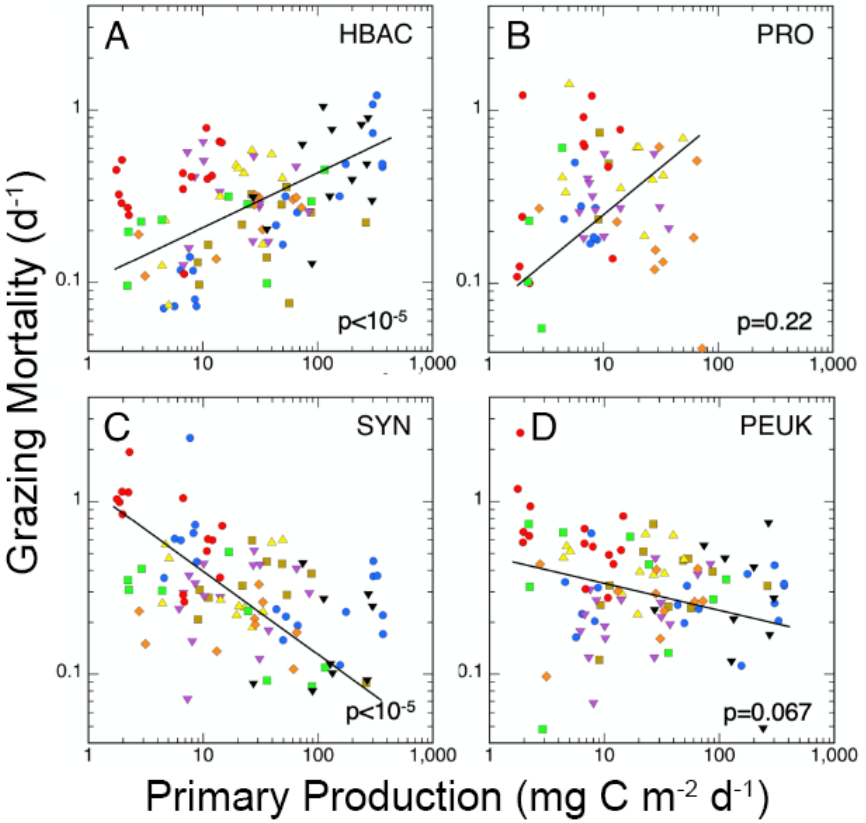


What advances are needed?

- Current autonomous platforms do not study the microbial loop
  - bgcArgo is really gcArgo
  - Imaging gliders (e.g., ZooGlider) and imaging floats (e.g., optical sediment traps) are still in their infancy and need higher resolution to resolve microbes
- Next-generation autonomous platforms are not ready yet (but deserve substantial investment)
  - Low-powered, high-resolution imaging (e.g., Imaging Flow CytoBot) coupled with onboard machine-learning
  - Autonomous collection (and sequencing?) of DNA and RNA
- **Ship-based process studies and time-series observations remain crucial**
  - **-omics & imaging paired with rate measurements**

Taxon-specific variability in protistan grazing across a productivity gradient



Landry et al. (2023, PNAS)

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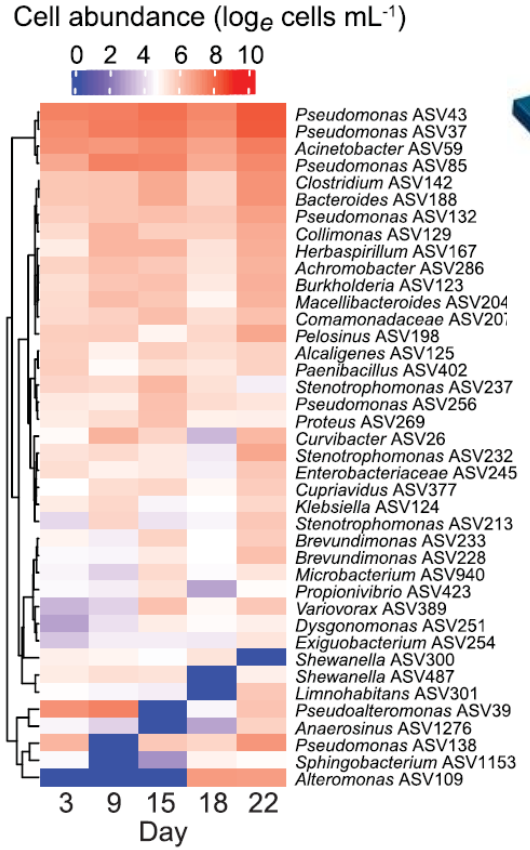
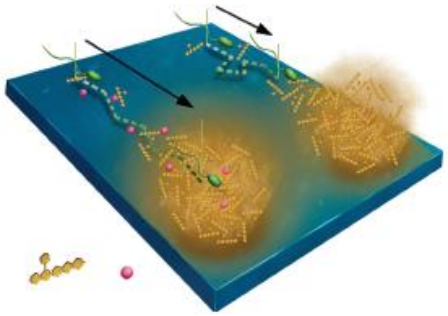
Taxon-specific bacterial chemotaxis towards complex polysaccharides





Clerc et al. (2023, Nat. Comm.)

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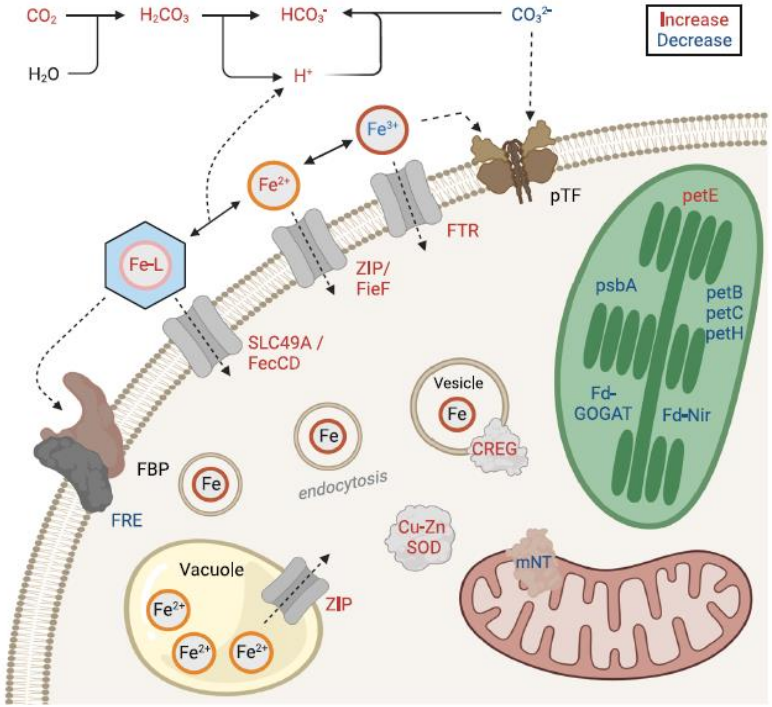
Diatom cellular-level responses to ocean acidification



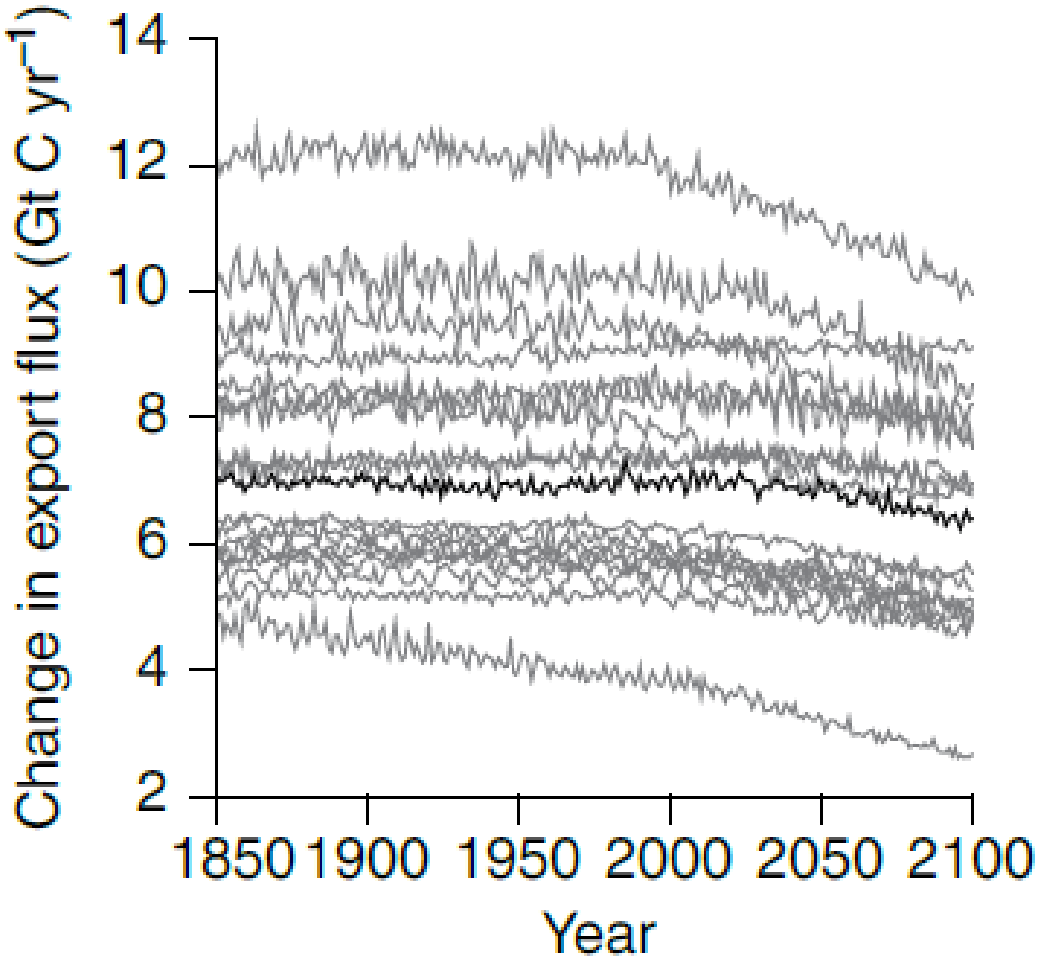
Lampe et al. (2023, Nat. Comm.)

What advances are needed?

- Need to synthesize these micro-scale results into process-level understanding of how biogeochemical function varies in time and space

Why should you care?
Part I: The oceans and carbon

- Ocean models predict future weakening of the biological carbon pump
  - But differ wildly in their current estimates of its magnitude
  - And often miss mechanisms that are observed in time-series studies
    - *Thalassiosira* in the California Current
    - C:P stoichiometric changes in the Sargasso Sea
    - Nitrogen fixation in the North Pacific Subtropical Gyre



Henson et al. (2022, Nat. Geo)

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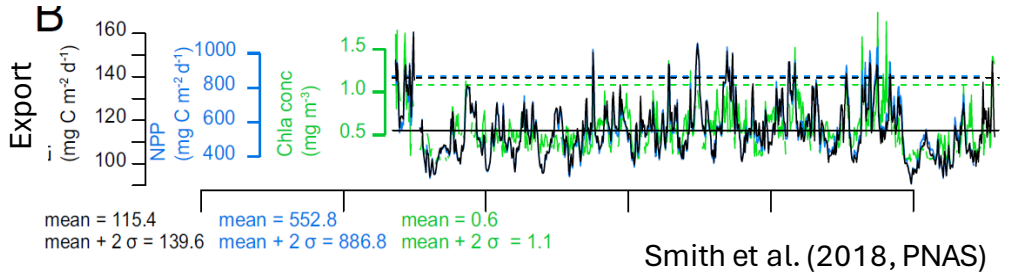
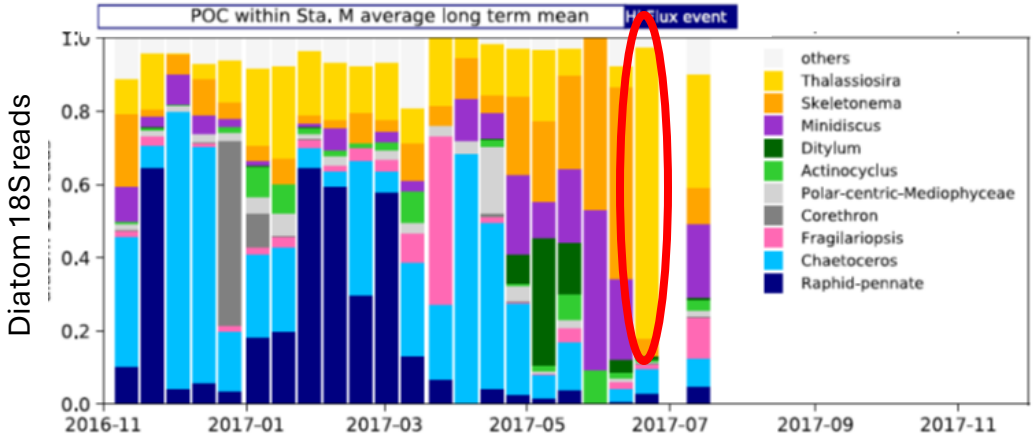
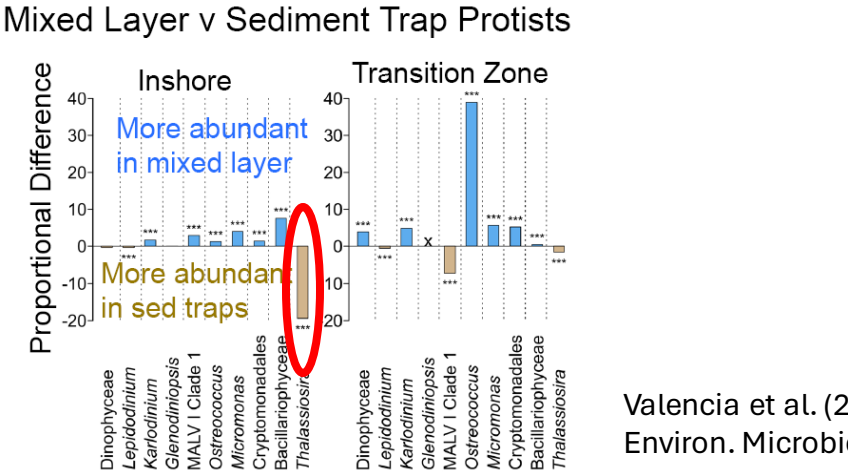


Smith et al. (2018, PNAS)



Preston et al. (2019, DSR2)



Valencia et al. (2021, Environ. Microbiol.)

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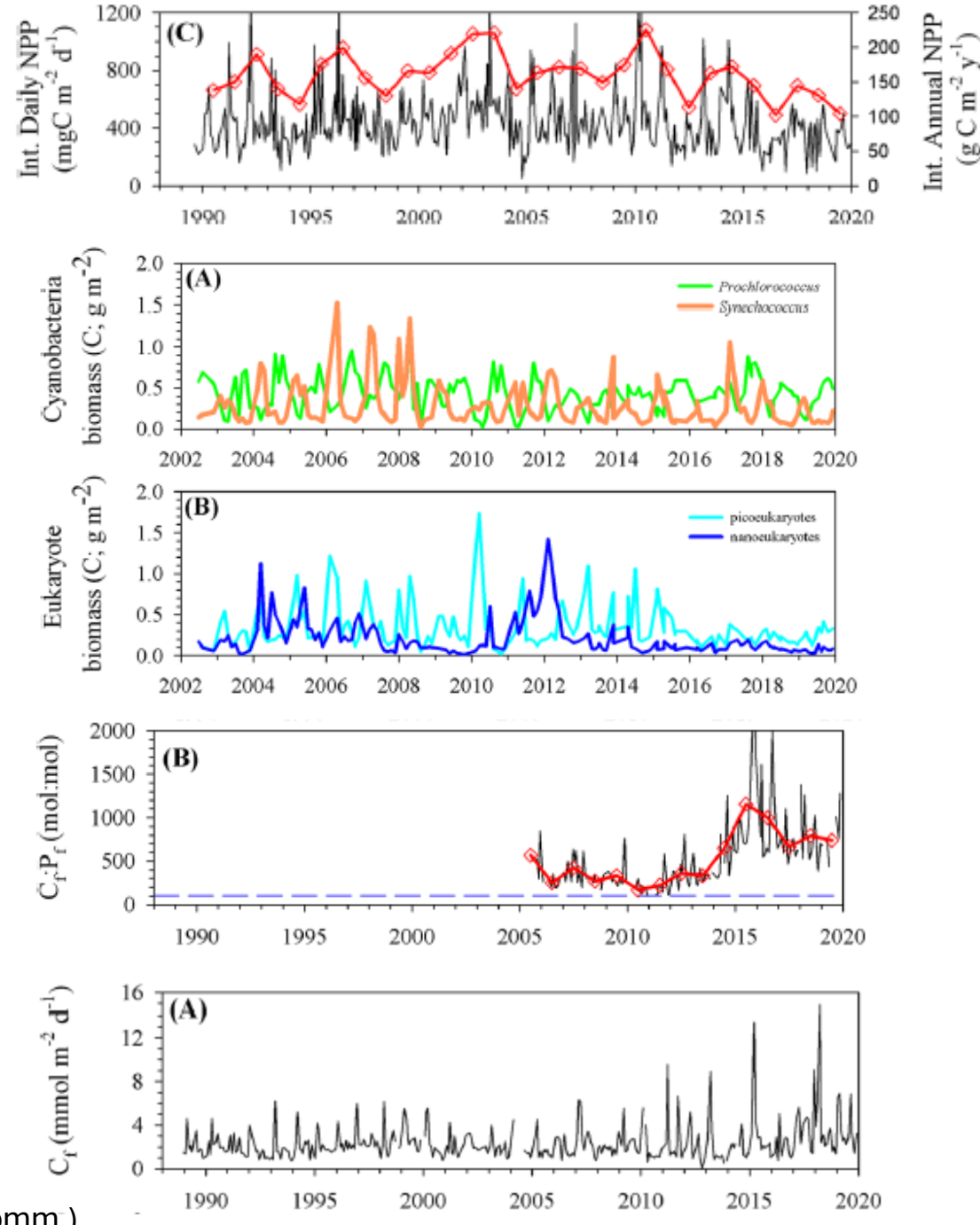

Lomas et al. (2021, Nat. Comm.)

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    - *Thalassiosira* in the California Current
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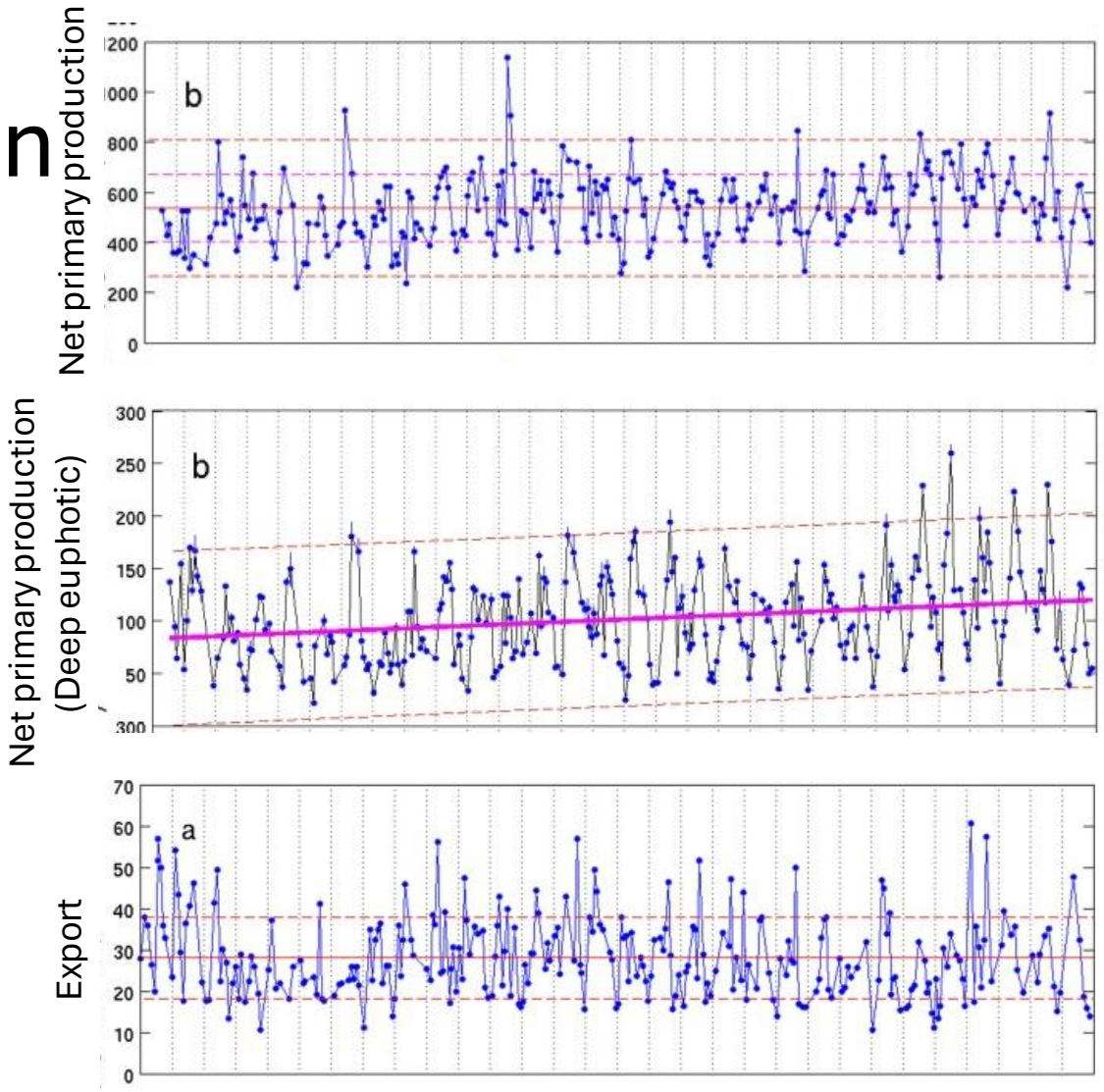
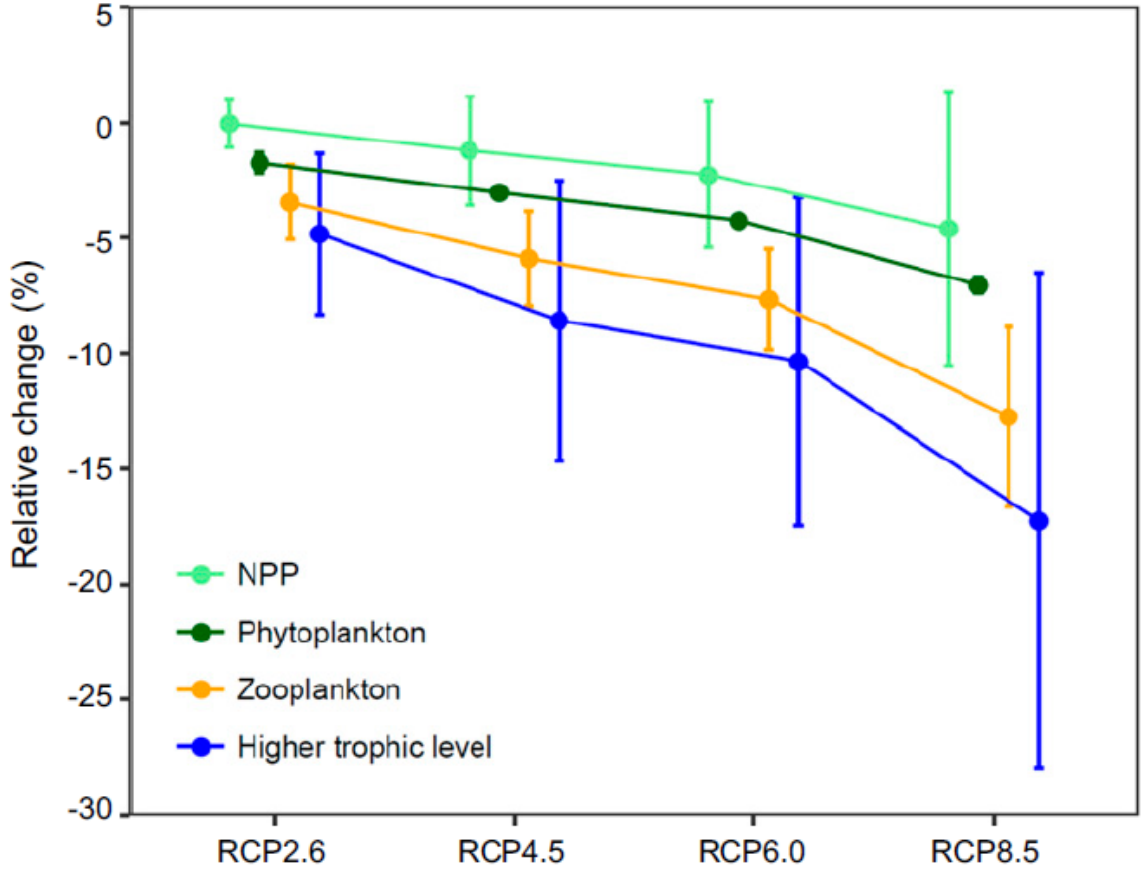
    - **Increasing primary production in the North Pacific Subtropical Gyre (iron supply & nitrogen fixation?)**



Karl et al. (2021, PinO)

Why should you care?
Part II: The oceans and food supply

- Ocean models predict that future declines in phytoplankton biomass will be *amplified* at higher trophic levels
  - Substantial declines in fisheries production
  - Caused (in part) by food chain elongation driven by a strengthened microbial loop
- But CMIP-class ocean models do not explicitly simulate the microbial loop or food-web reorganization due to climate change

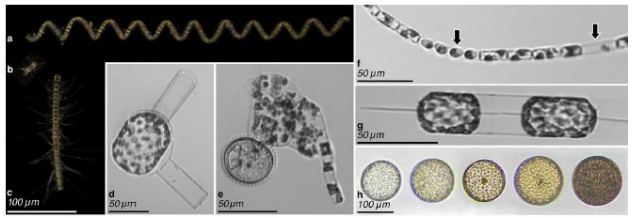


Lotze et al. (2019, PNAS)

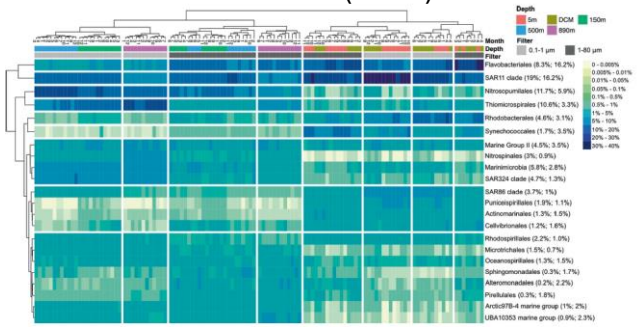
Future modeling advances

- **Adaptive parameterization**
  - Machine-learning (artificial-intelligence) approaches to variable parameterization
  - Massively multi-parameter ensemble modeling
  - “Emergent-properties” models that allow community evolution through the simulation of thousands of stochastically parameterized microbes
  - **Mechanistic understanding of how integrated properties of microbial loop dynamics underlie regional/temporal biogeochemical variability**
- **Close integration with observations**
  - How do we map high-resolution imaging data and genetic sequencing observations to our model structures?
  - Requires standardization of observational methodology

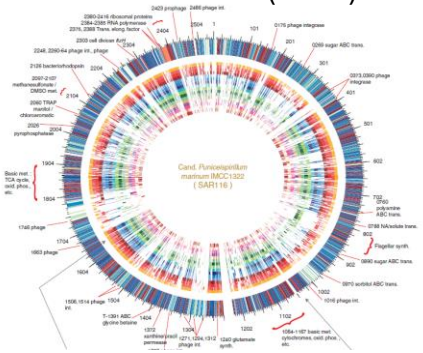
Orenstein et al. (2022)



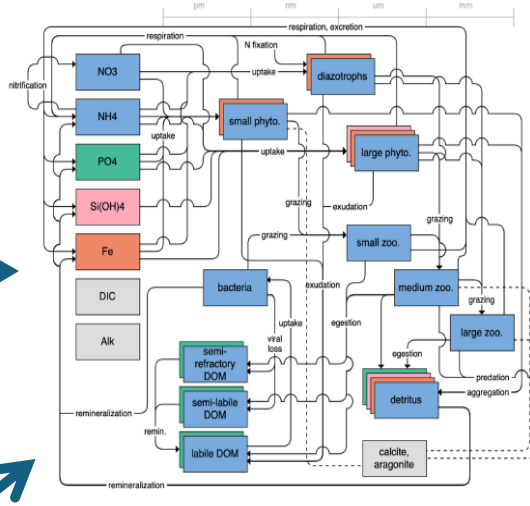
Yeh & Fuhrman (2022)



Gifford et al. (2014)



COBALT Model



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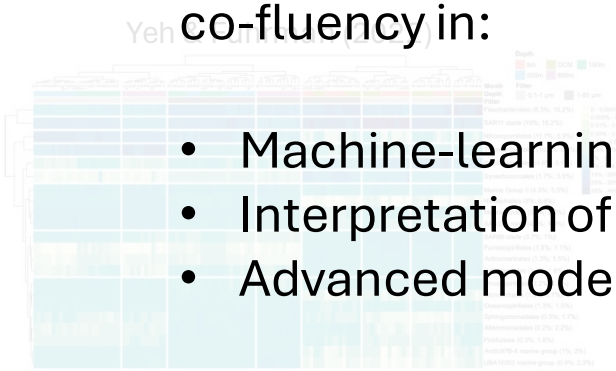

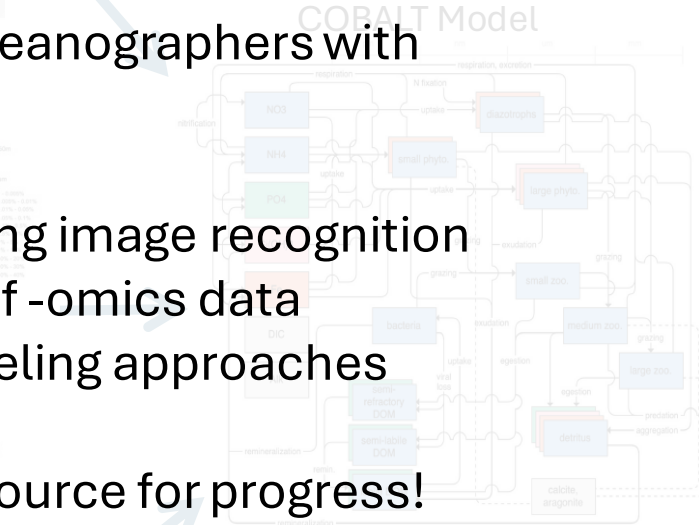

A generation of oceanographers with co-fluency in:

- Machine-learning image recognition
- Interpretation of -omics data
- Advanced modeling approaches

is a necessary resource for progress!

Partnerships

- NOAA fisheries – link microbial loop to ecosystem-based fisheries management
- NOAA & DOE climate modeling – microbial loop is crucial to efficiency of the biological carbon pump, but is mostly implicit in climate models and thus does not adapt dynamically to climate change
- NASA – PACE mission, etc.
- NSF Technology, Innovation, and Partnerships
  - Image processing & environmental sequencing are both “big data” frontiers
  - Ocean modeling is pushing the frontiers of computational feasibility
  - Microbial functional analyses yield diverse use cases
    - Environmental remediation (e.g., oil spills)
    - Marine carbon dioxide removal
    - Aquaculture
- NSF Biology – ability to investigate species-specific relationships suddenly positions plankton communities as ideal laboratory for investigating ecological principles
  - Division of environmental biology
  - Biodiversity on a changing planet
  - Accelerating computing-enabled scientific discovery
  - Organismal response to climate change