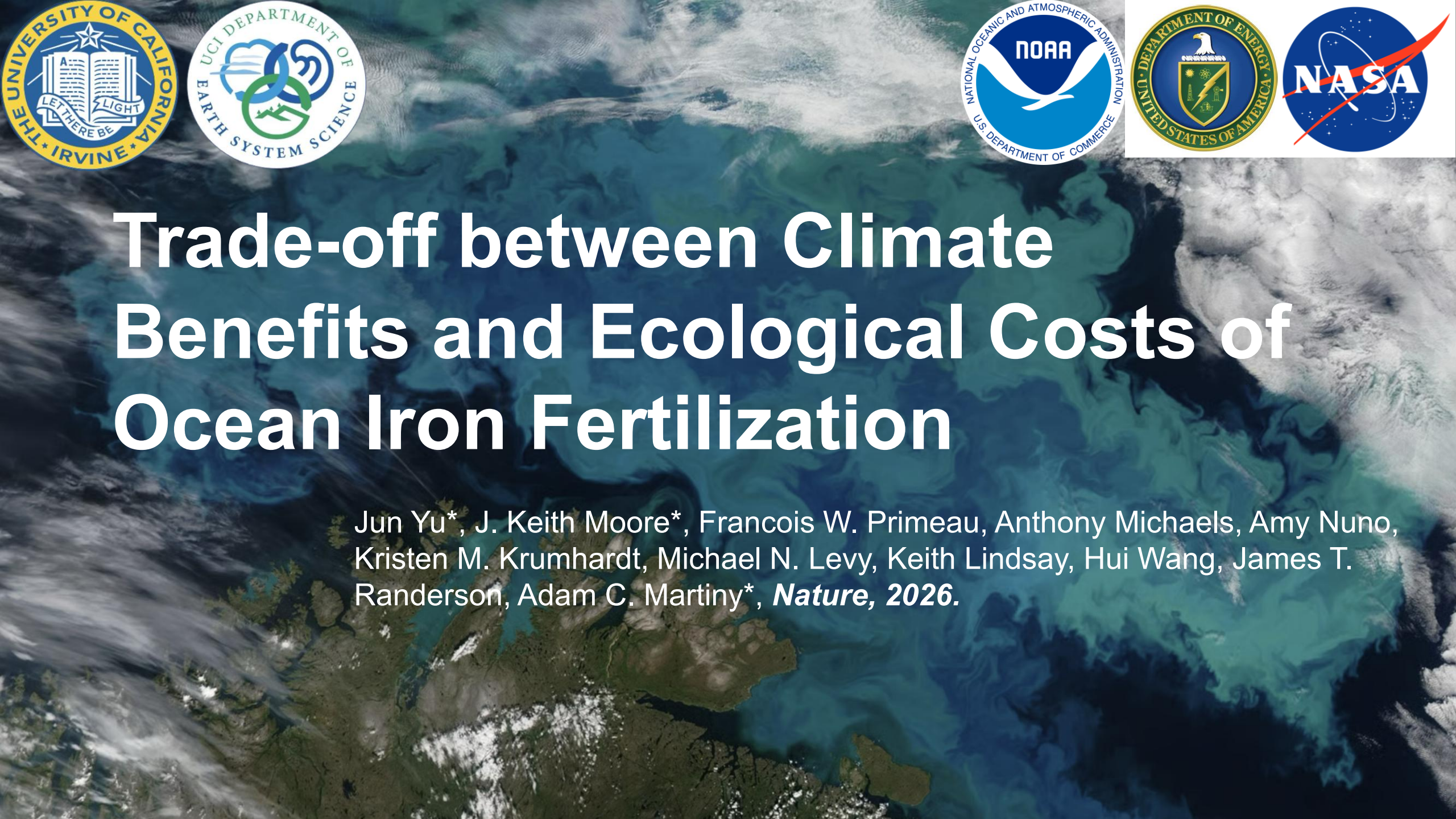


Trade-off between Climate Benefits and Ecological Costs of Ocean Iron Fertilization

Jun Yu*, J. Keith Moore*, Francois W. Primeau, Anthony Michaels, Amy Nuno, Kristen M. Krumhardt, Michael N. Levy, Keith Lindsay, Hui Wang, James T. Randerson, Adam C. Martiny*, ***Nature, 2026.***

Ocean Iron Fertilization (OIF): trade-off between carbon-efficiency vs. ecological impact

Key science questions from this study:

What is the net CDR from patch fertilization accounting for ”downstream” effects (in both space and time)?

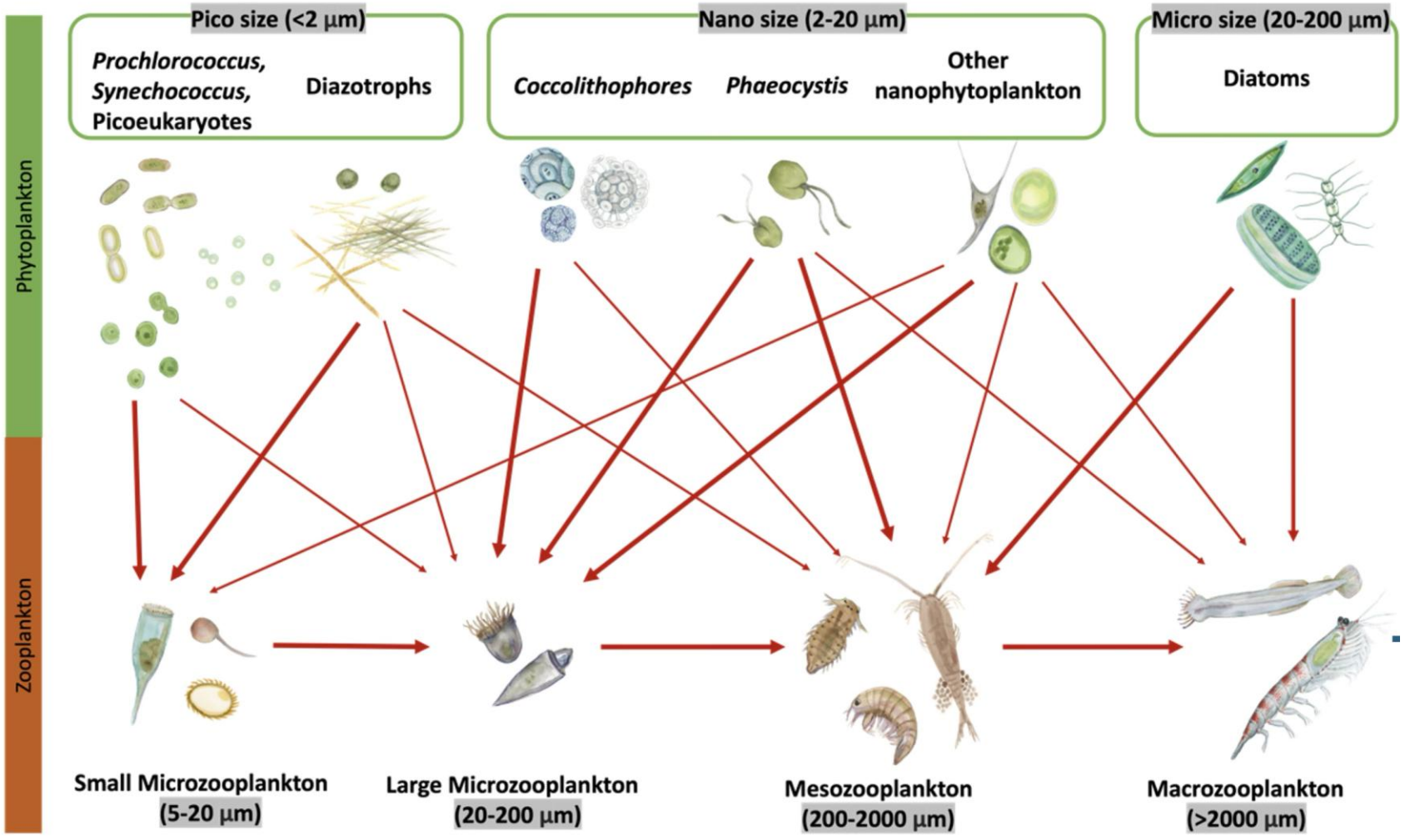
How much CO_2 is sequestered on climate relevant timescales?

What is the CDR capacity in different regions in this context?

Are there negative ecosystem impacts of CDR in different regions?

A next-generation ecosystem model (CESM2-8P4Z)

- **Joint-representation** of biodiversity and biogeochemistry.
- **Process-rich**:
  Expanded community composition (8P4Z) and subsequent impacts on:
  - size-related export efficiency,
  - dynamic phytoplankton resource demands with fully-variable C:N:P:Fe,
  - explicit representation of nitrogen fixation, denitrification, and calcification,
  - dynamic food webs with insight for impact on fisheries.



Yu et al., 2025, Simulating marine ecosystem dynamics and biogeochemical cycling with multiple plankton functional types. ***JAMES****, https://doi.org/10.1029/2024MS004521*

Phytoplankton acclimate to available nutrients by modifying their nutrient/C cell quotas

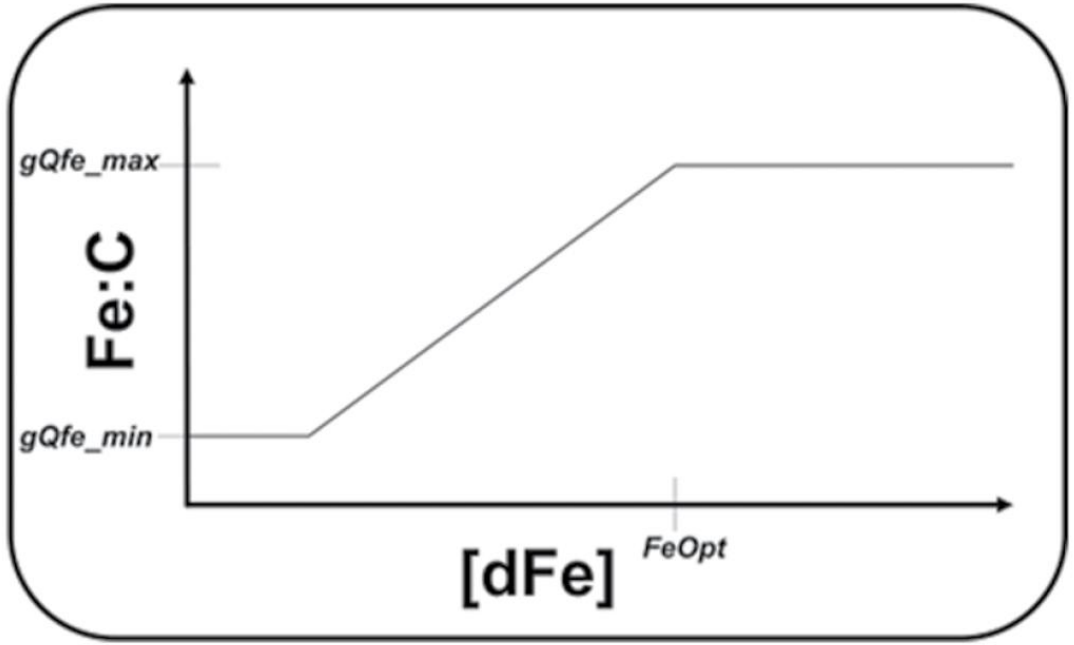
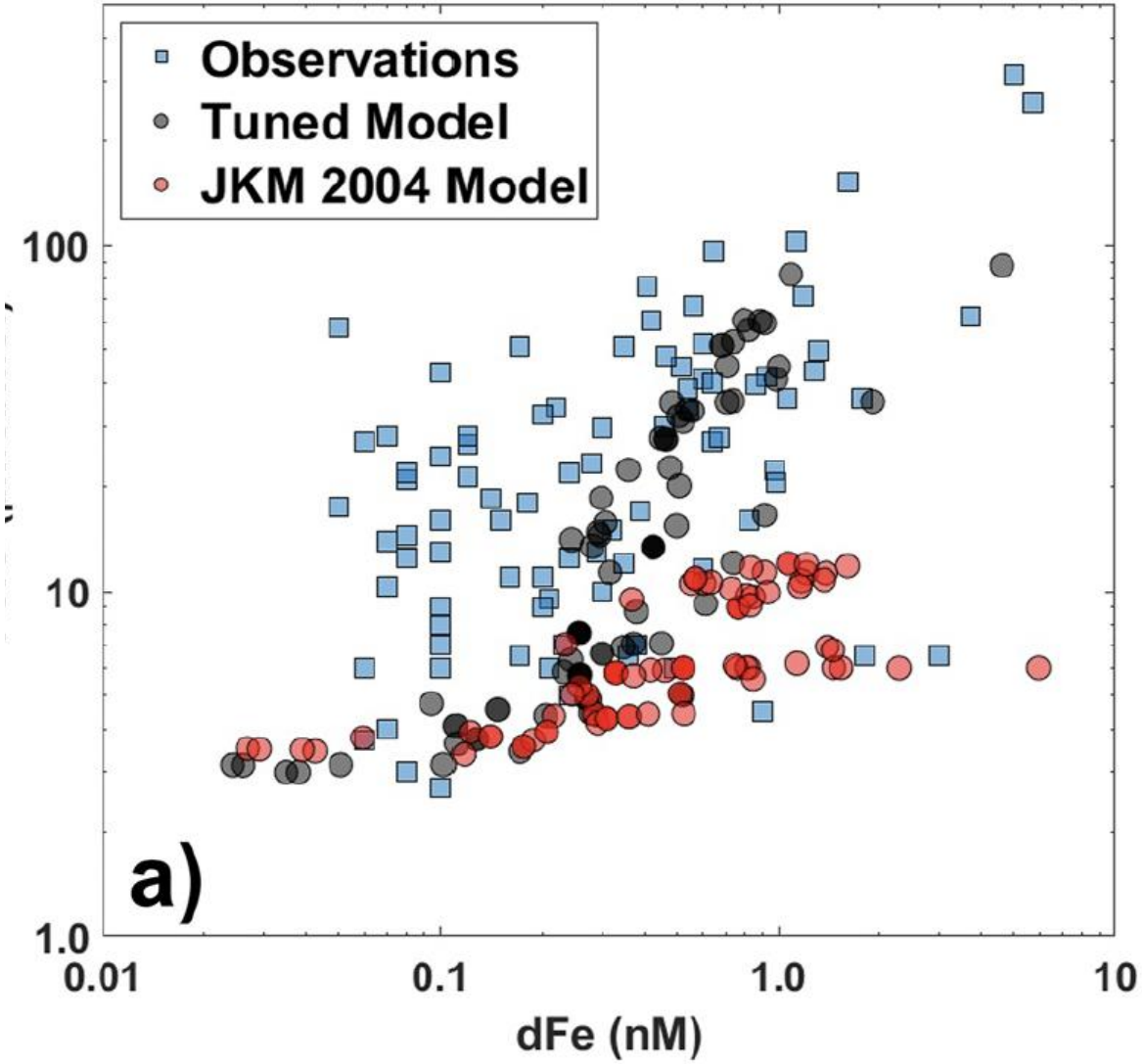


Figure 1. Phytoplankton Fe:C ratio for new growth as a function of dissolved iron. FeOpt determines the dissolved ambient iron concentration at which phytoplankton Fe:C reaches its maximum value (gQFe_max). Fe:C varies linearly with dissolved iron concentration between the prescribed, group-specific maximum (gQFe_max) and minimum (gQfe_min) quotas.

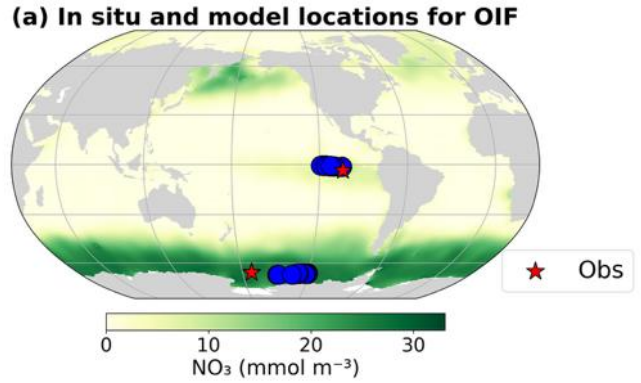


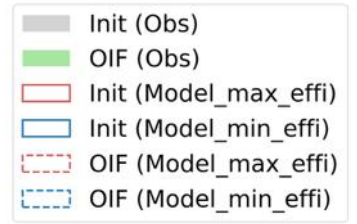
The model has dynamic stoichiometry for all growth-limiting nutrients, including: Fe/C, N/C, P/C, and Si/C (Si only for diatoms) (Wiseman et al. 2023).

Yu et al., 2025, Simulating marine ecosystem dynamics and biogeochemical cycling with multiple plankton functional types. ***JAMES****, https://doi.org/10.1029/2024MS004521*

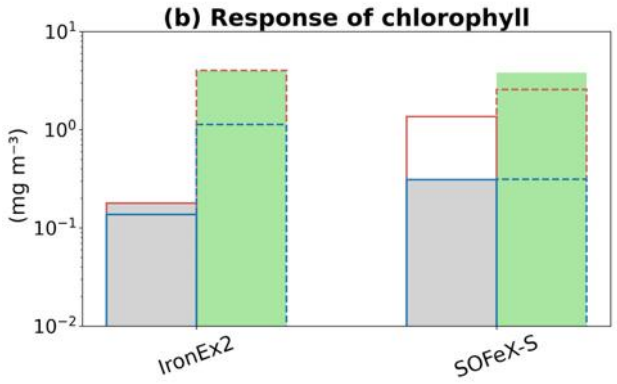
Model captures the response of past *in situ* OIFs

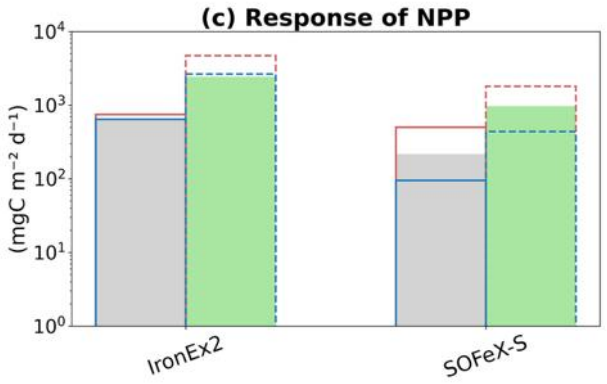
One month of grid-scale OIF

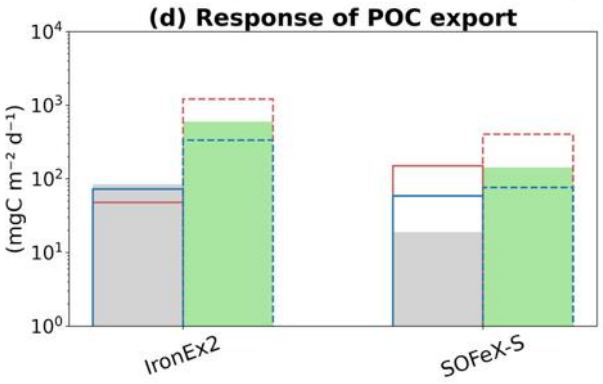




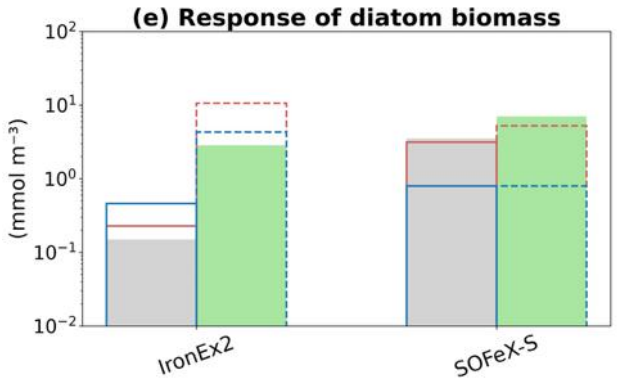
Biogeochemical response (Chl, NPP and C export):

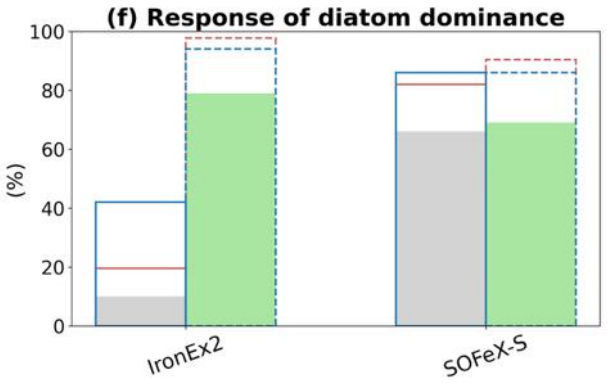


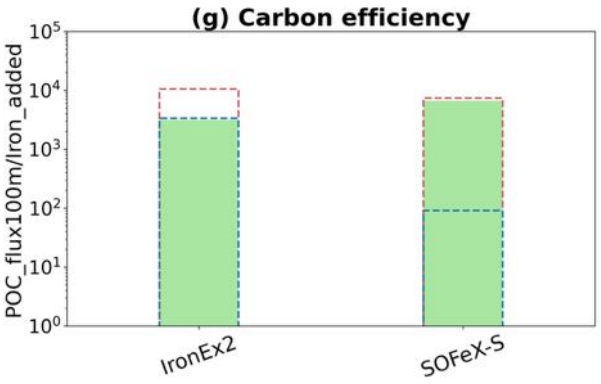




Ecological shift:

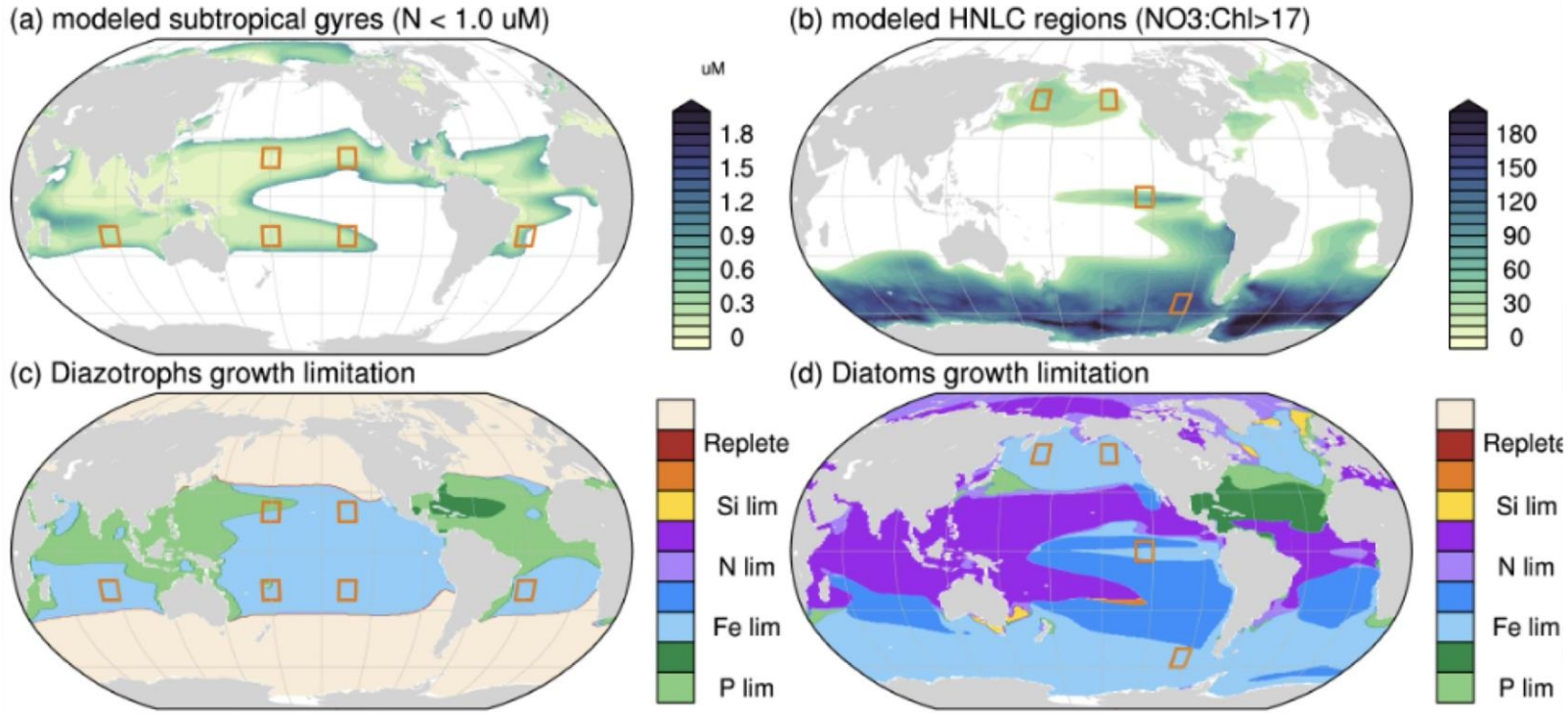




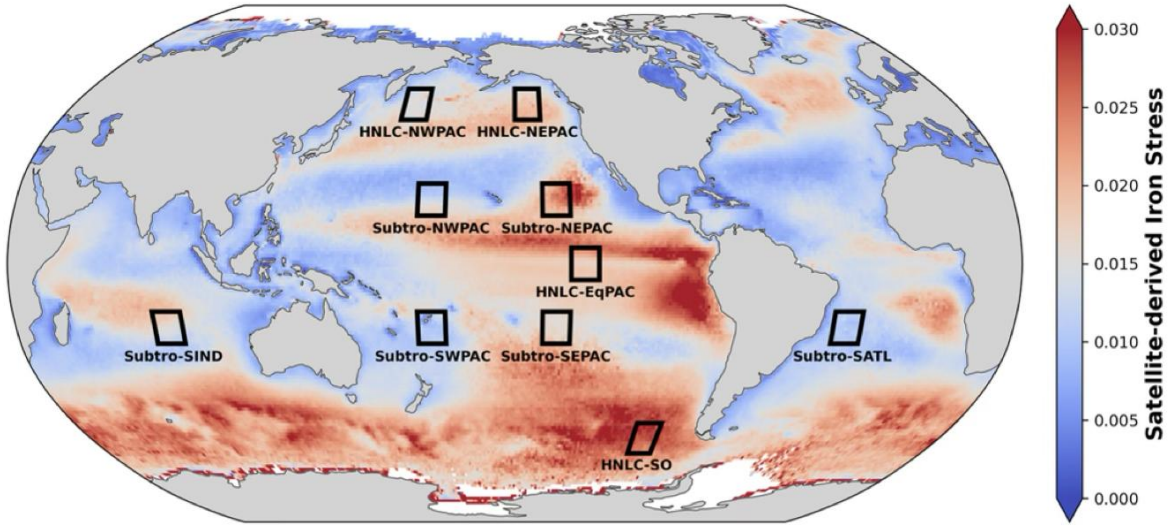


10x10 degree fertilization for 60 years, followed by 60 years without fertilization

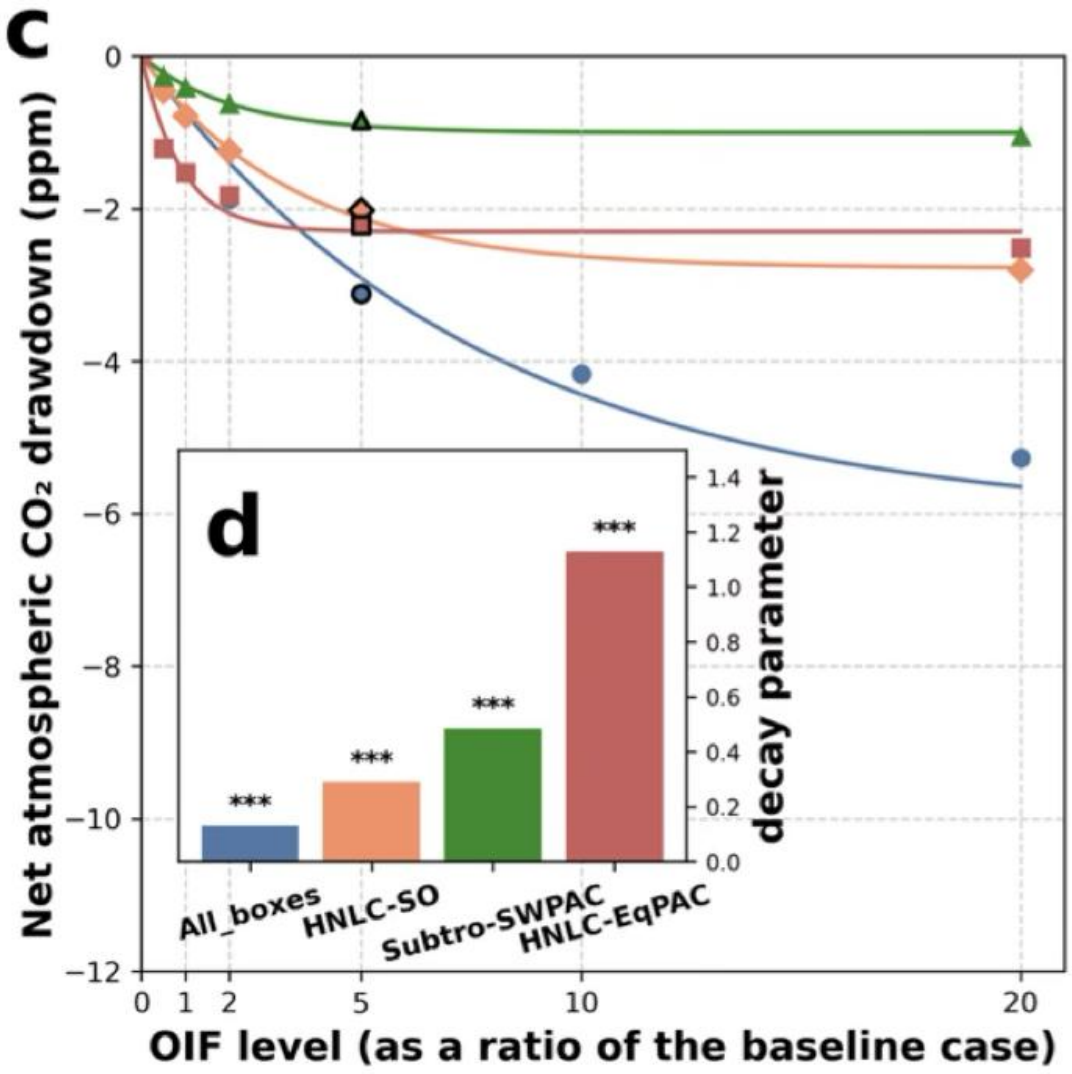
- 10 regions (4 HNLC and 6 oligotrophic sites).
- Baseline OIF (1x): 10% of global atmospheric iron deposition (~5 Gmol Fe/year) .
- Use 5× and 20× as the baseline for the medium and upper bounds.



10x10 degree fertilization for 60 years



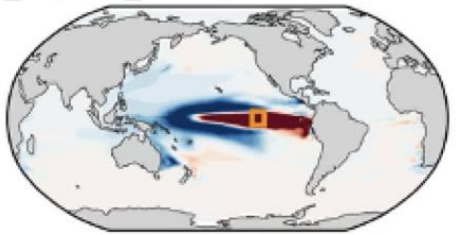
- 10 regions (4 HNLC and 6 oligotrophic sites).
- **Top efficiency places:**
  HNLC-EqPAC, Southern Ocean,
  Subtropical SWPAC,
  and mild global fertilization;
- Fertilization efficiency sharply declines with OIF intensity.



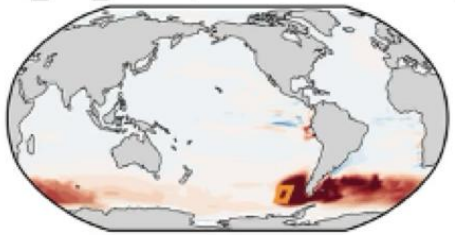
The non-local downstream effect

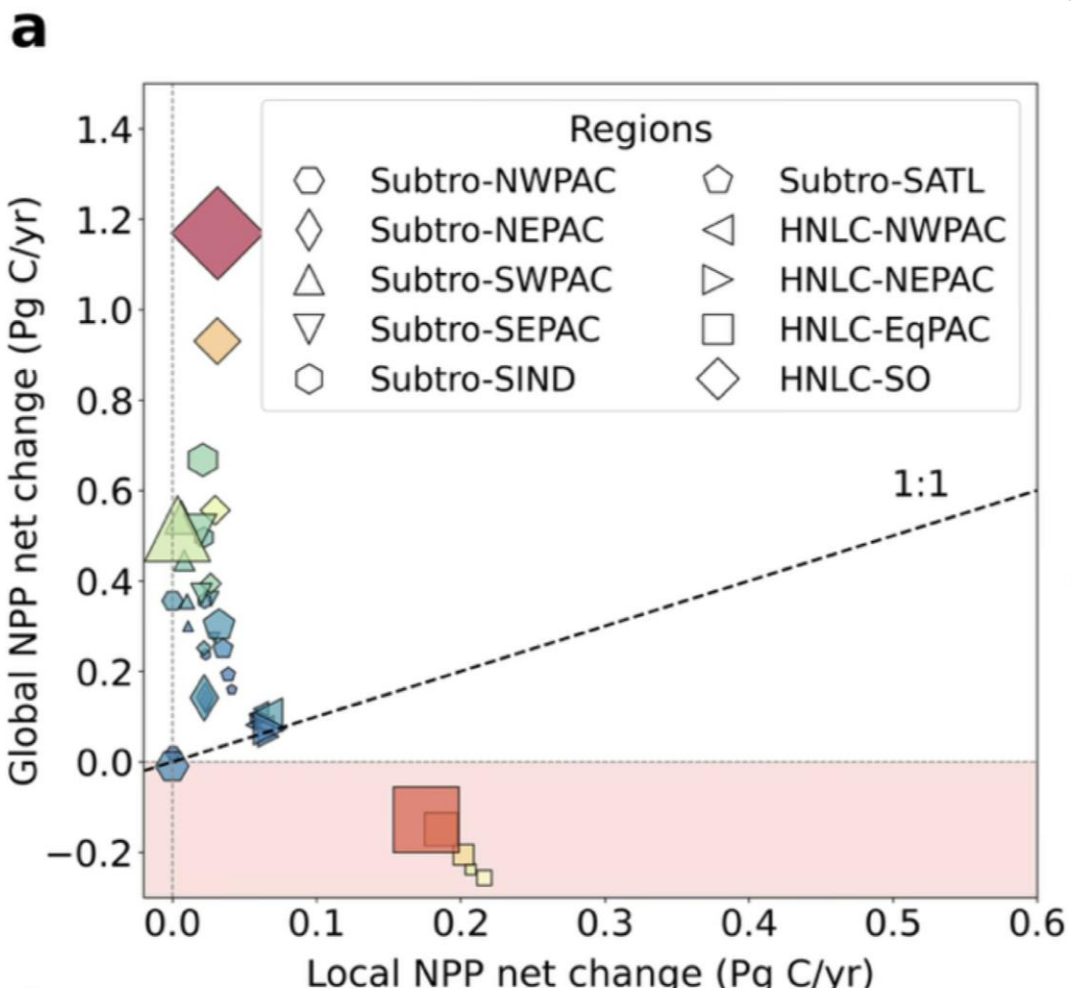
NPP changes:

(i) HNLC_EQPAC_x5.0 (ΔNPP = -0.15 Pg C/yr)



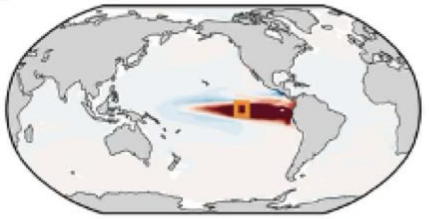
(k) HNLC_SO_x5.0 (ΔNPP = +0.93 Pg C/yr)



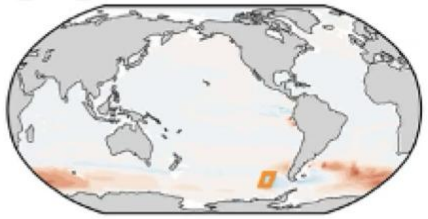


POC flux at 1000m changes:

(k) HNLC_EQPAC_x5.0 (Δflux = +0.050 Pg C/yr)



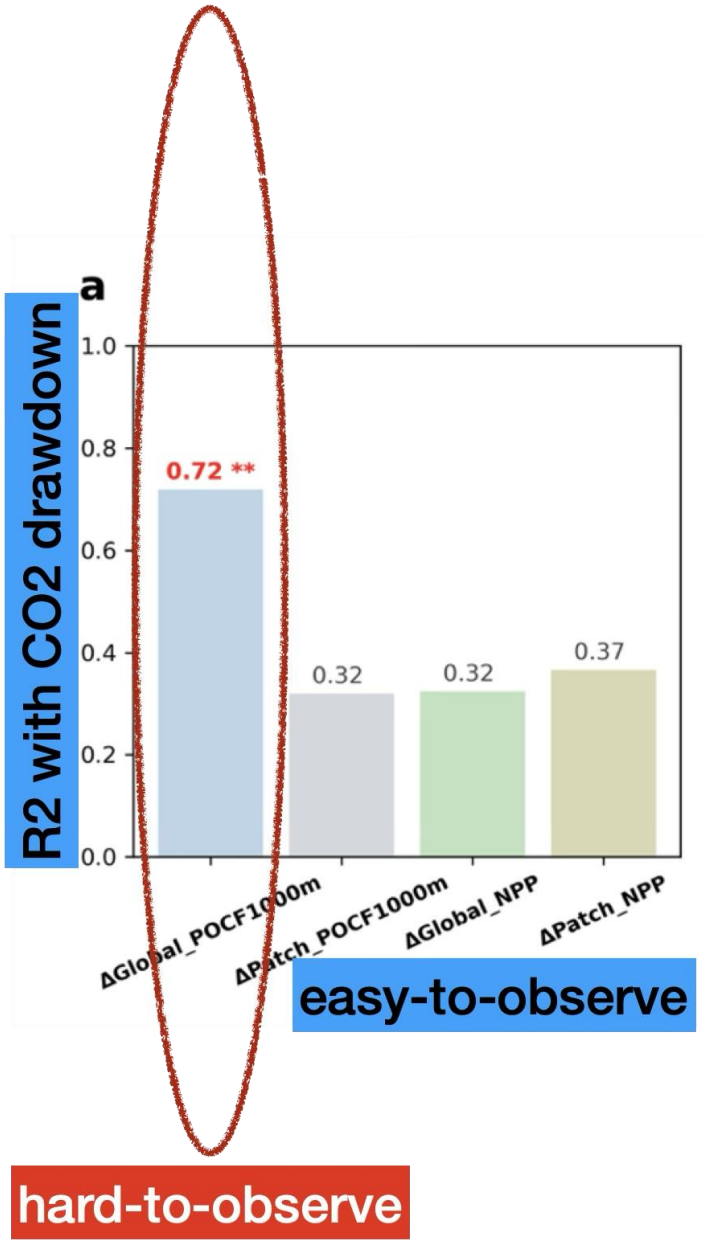
(l) HNLC_SO_x5.0 (Δflux = +0.024 Pg C/yr)



Challenges for carbon crediting of OIF

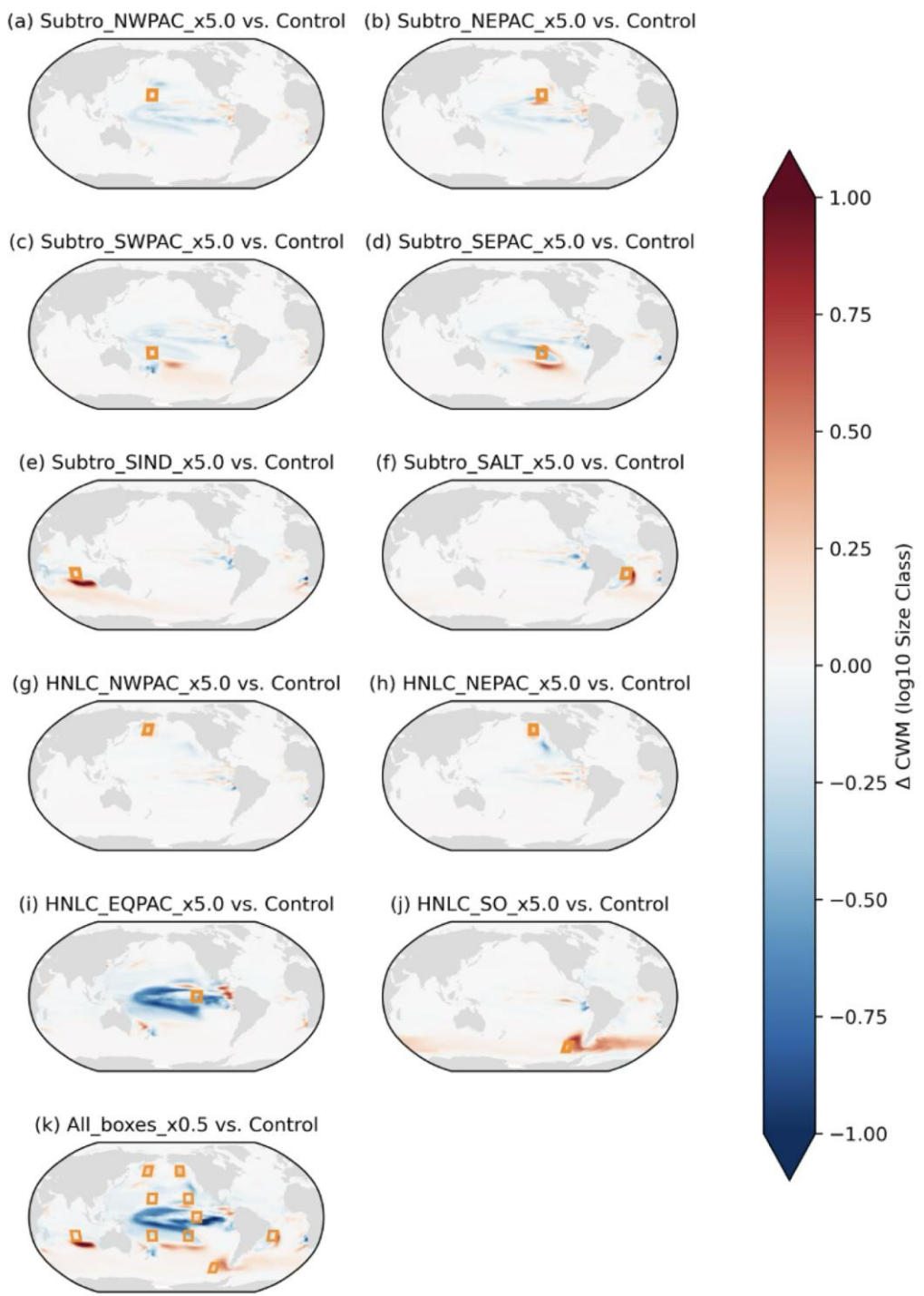
- **Practical conundrum**: easy-observable indicators are poor proxies for credible CO_2 removal, whereas the decisive metric requires technically difficult global-scale observations;

- Nearly impossible to separate multiple ongoing fertilization efforts in similar regions.



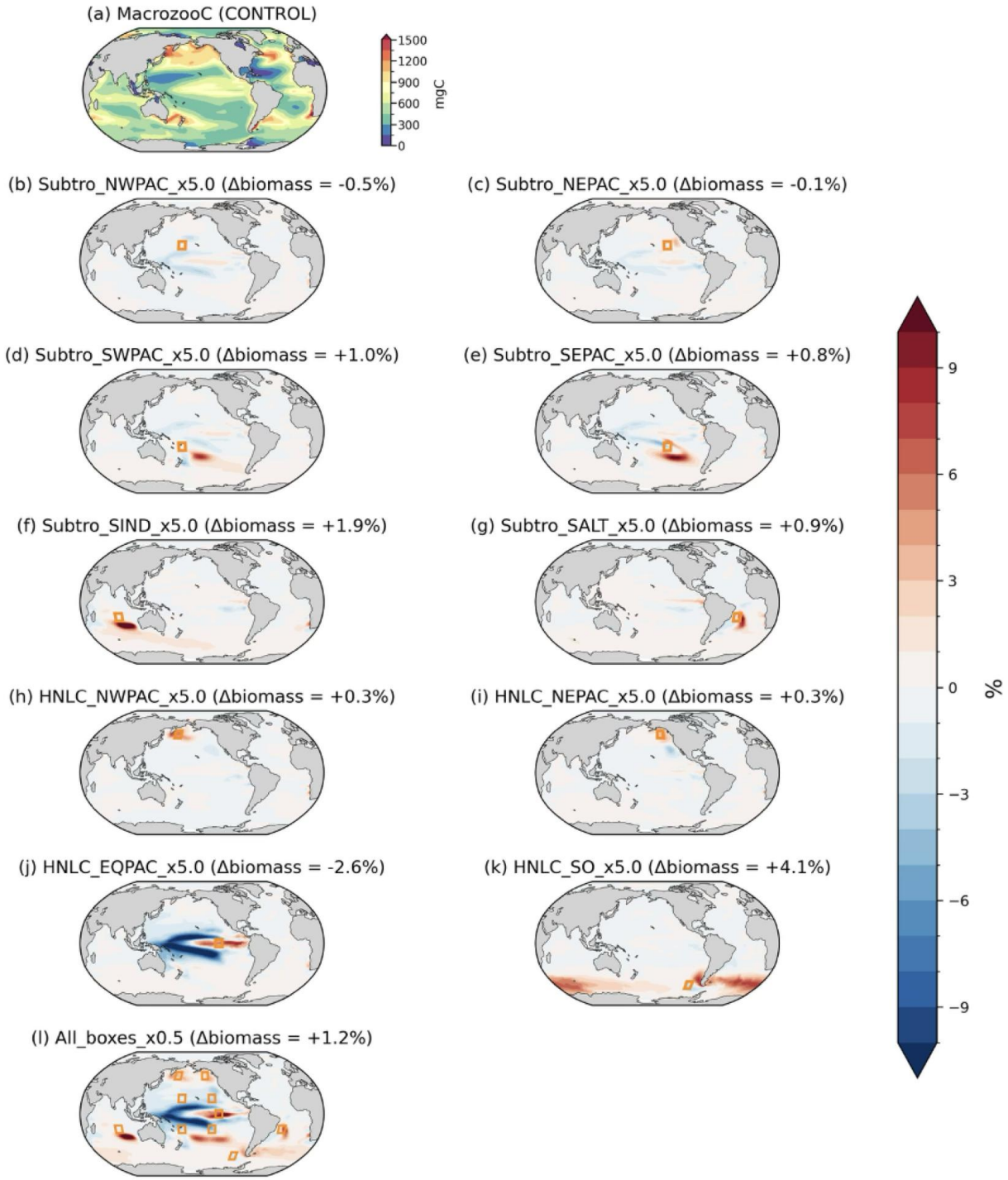
Ecological costs

- Ecosystem structure shifts to a smaller size when OIF in the central Pacific, but to a larger size at higher latitudes;



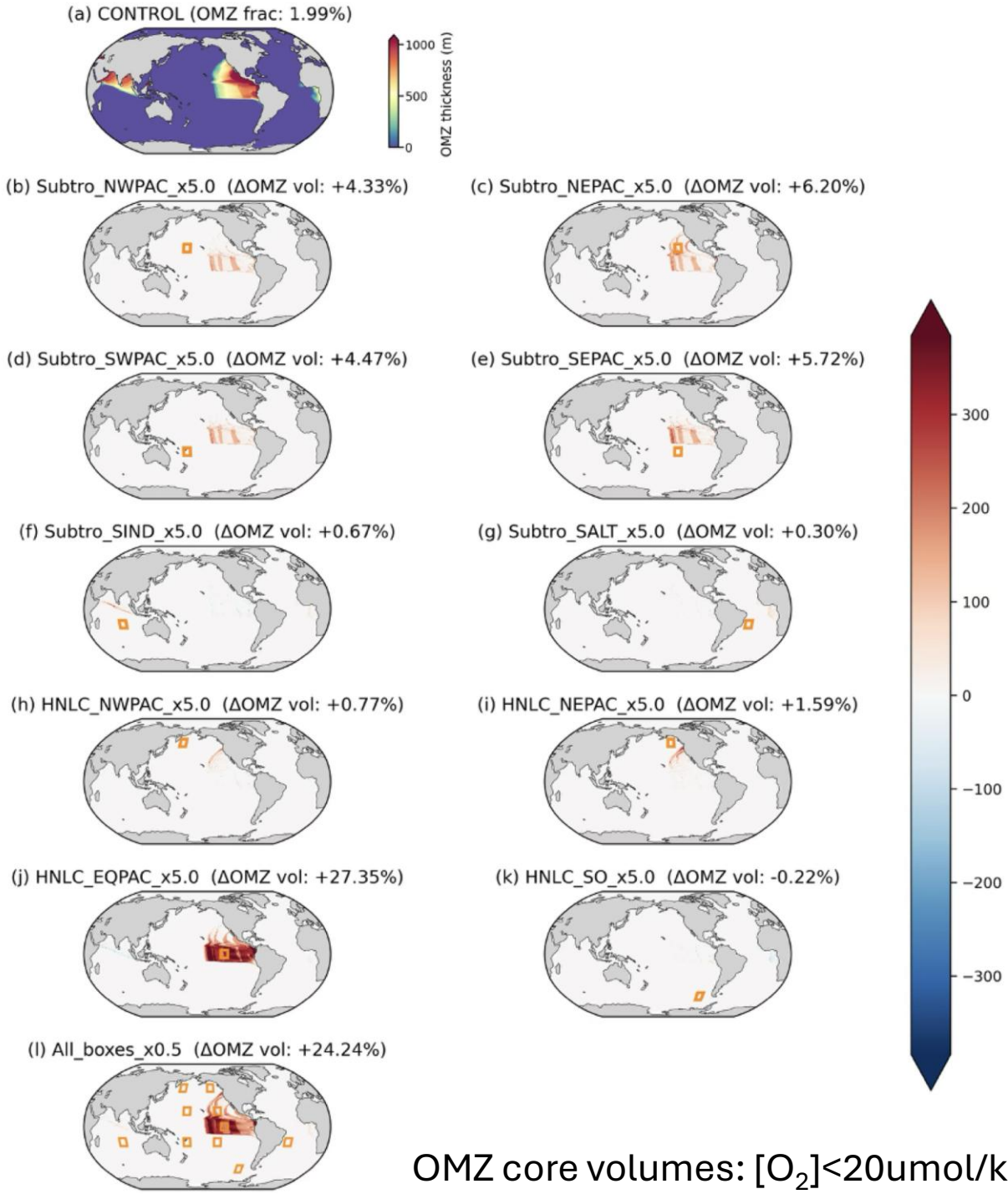
Ecological costs

- Ecosystem structure shifts to a smaller size when OIF in the central Pacific, but to a larger size at higher latitudes;
- Impact of size-shifting propagates to higher trophic levels;



Ecological costs

- Ecosystem structure shifts to a smaller size when OIF in the central Pacific, but to a larger size at higher latitudes;
- Impact of size-shifting propagates to higher trophic levels;
- Closer to the main OMZs, more denitrification and OMZ expansion.
- Increasing denitrification balanced the increasing N fixation in the gyre fertilizations.
- Iron added in the gyres, quickly spread into the adjacent OMZ regions, increasing export and driving the increasing denitrification.

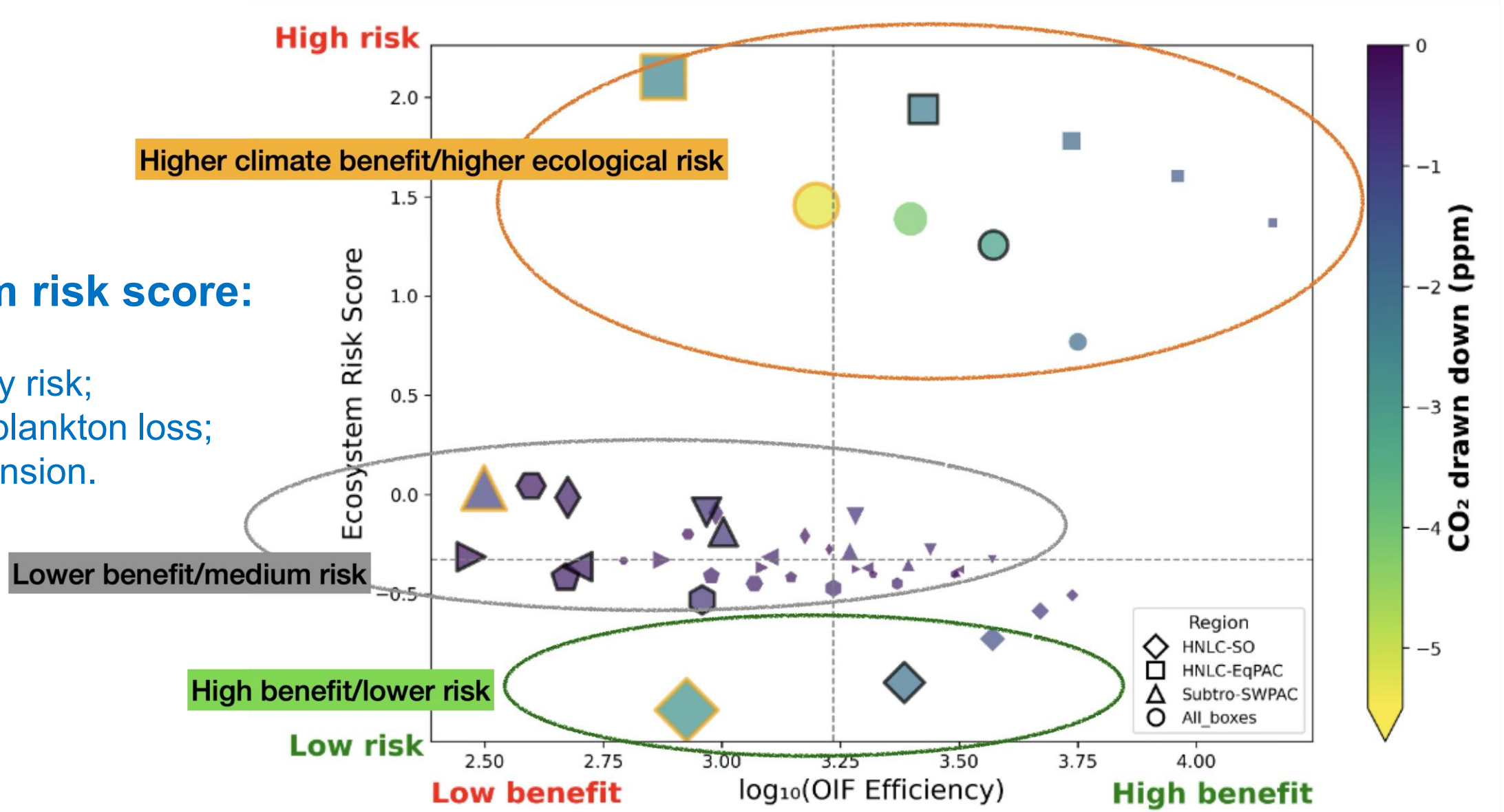


OMZ core volumes: $[O_2]$<20umol/k

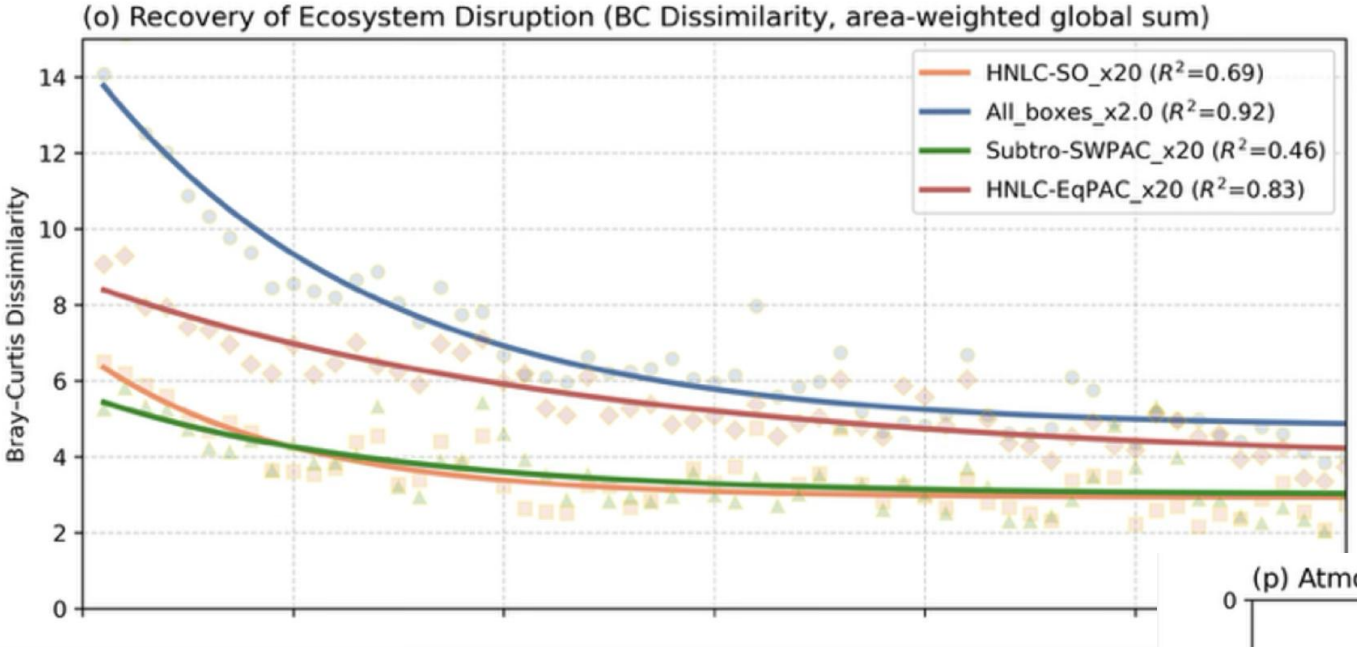
Climate-ecosystem trade-off

Ecosystem risk score:

- Biodiversity risk;
- Macrozooplankton loss;
- OMZ expansion.

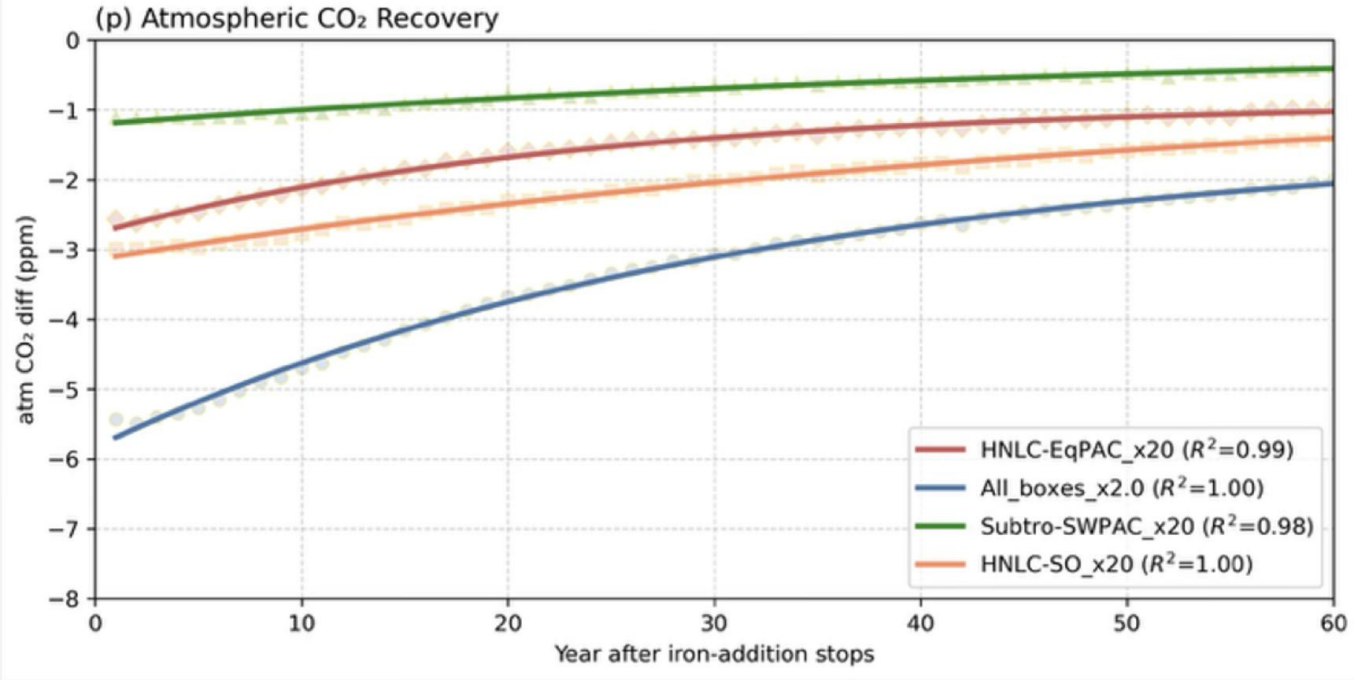


The post-fertilization recovery



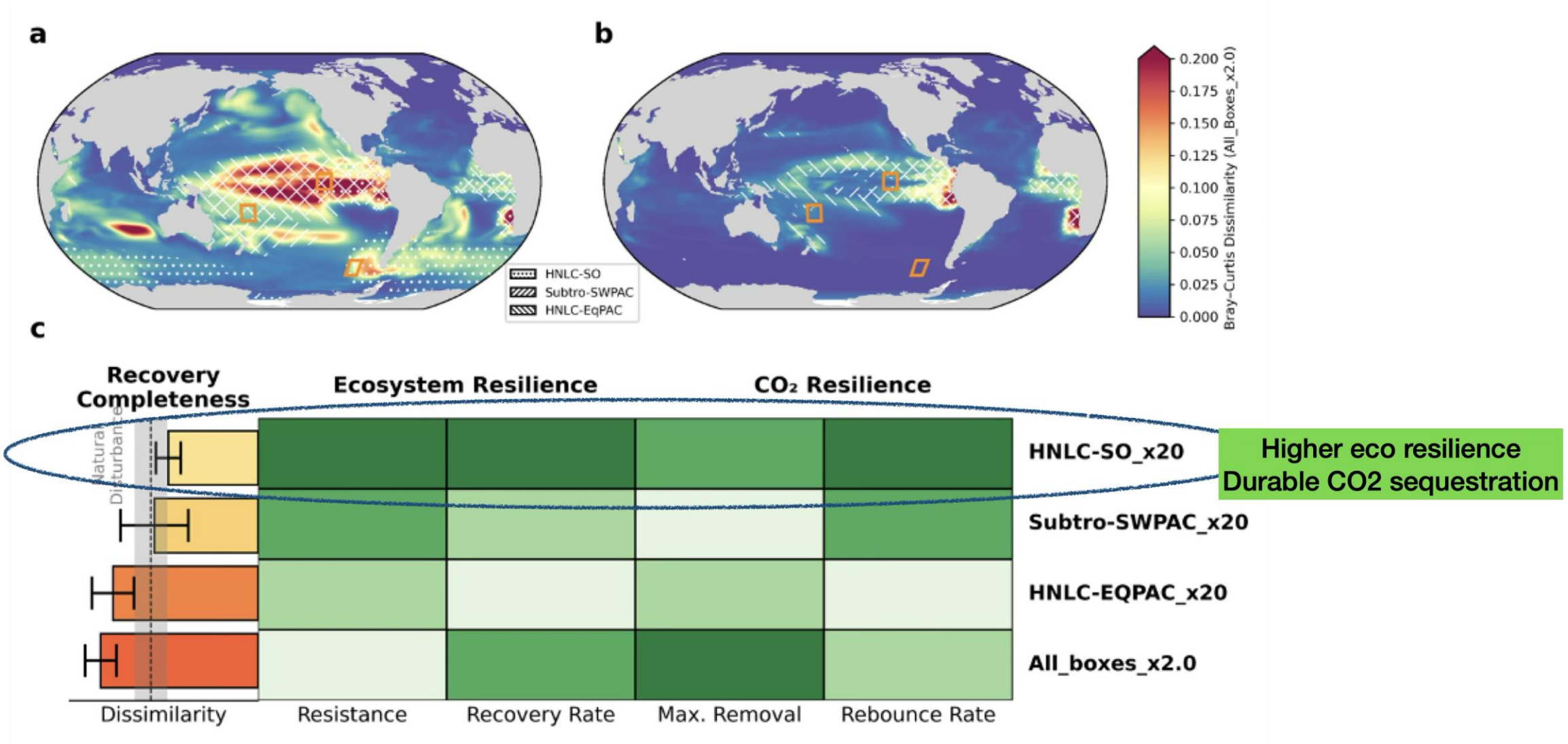
At all box locations, about half of the CO_2 stored under 60 years of fertilization leaked back to the atmosphere!

At all box locations, except the EqPac, the plankton community was similar to the original community,
60 years after fertilization stopped.



Resilience:

resistance (capacity to withstand disturbance) + recovery (return to baseline)



Conclusions

- Continuous OIF yields <1 $GtCO_2$/year, with **a global footprint** of biogeochemical and ecological impacts from relatively small fertilization areas.
- **Three trade-off tiers:**
  - Southern Ocean (higher efficiency / lower risk)
  - Equatorial Pacific and global fertilization (higher efficiency / higher risk)
  - and subtropic ocean (lower efficiency / medium risk).
- Carbon crediting challenged by non-local impacts and weak correlations with easy-to-measure indicators.
- All fertilizations in the gyres led to increasing N-fixation and denitrification with small changes in atmospheric CO_2.
- In the equatorial Pacific, increasing export depletes nutrients over time, exporting out of the nutrient trapping zone in the eastern EqPac. There are large negative ecological impacts, declining NPP, macrozooplankton biomass, and expanded OMZs and increased denitrification. Some of the added iron is retained for a long time in the trapping zone.
- In the Southern Ocean, lower risks with moderate carbon storage.