Potential risks and benefits of mCDR at the pilot and Gt-scale - ocean iron as a case study

Ken Buesseler
Senior Scientist, WHOI
Executive Director, ExOIS

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What is the scale of the problem?

-humans have released about 400 Gt carbon (≈1,500 Gt $CO_{2\text{-eq}}$)

Deep ocean holds
40,000 Gt Carbon

Small amounts of iron enhance phytoplankton growth in some locations

"Just add iron" 13 ocean experiments 1993-2009

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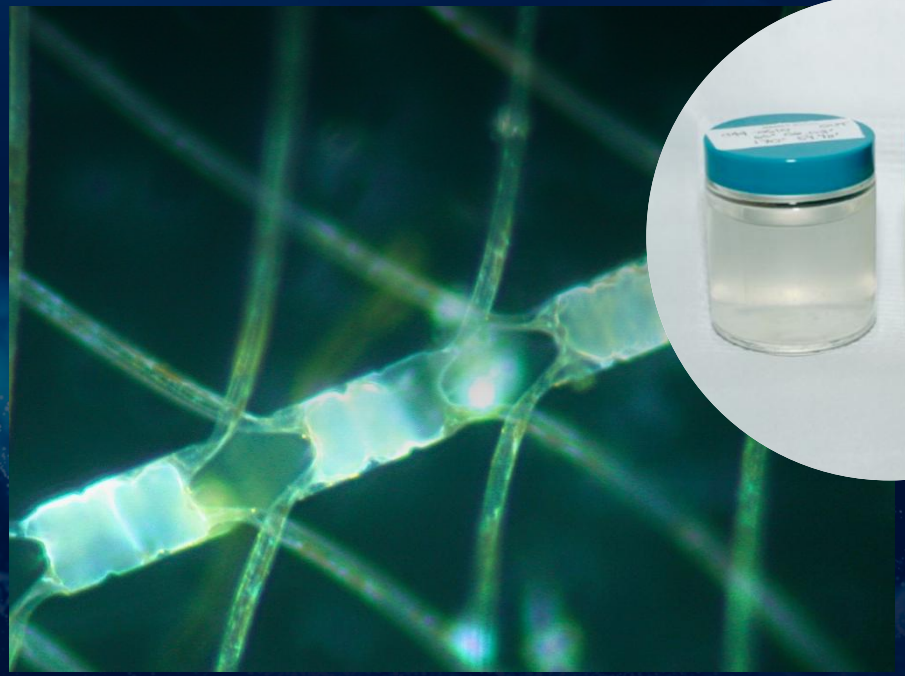
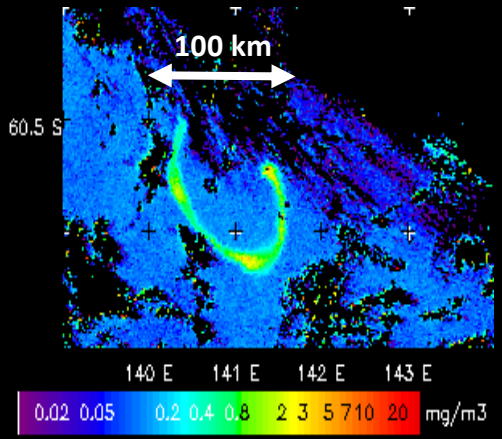
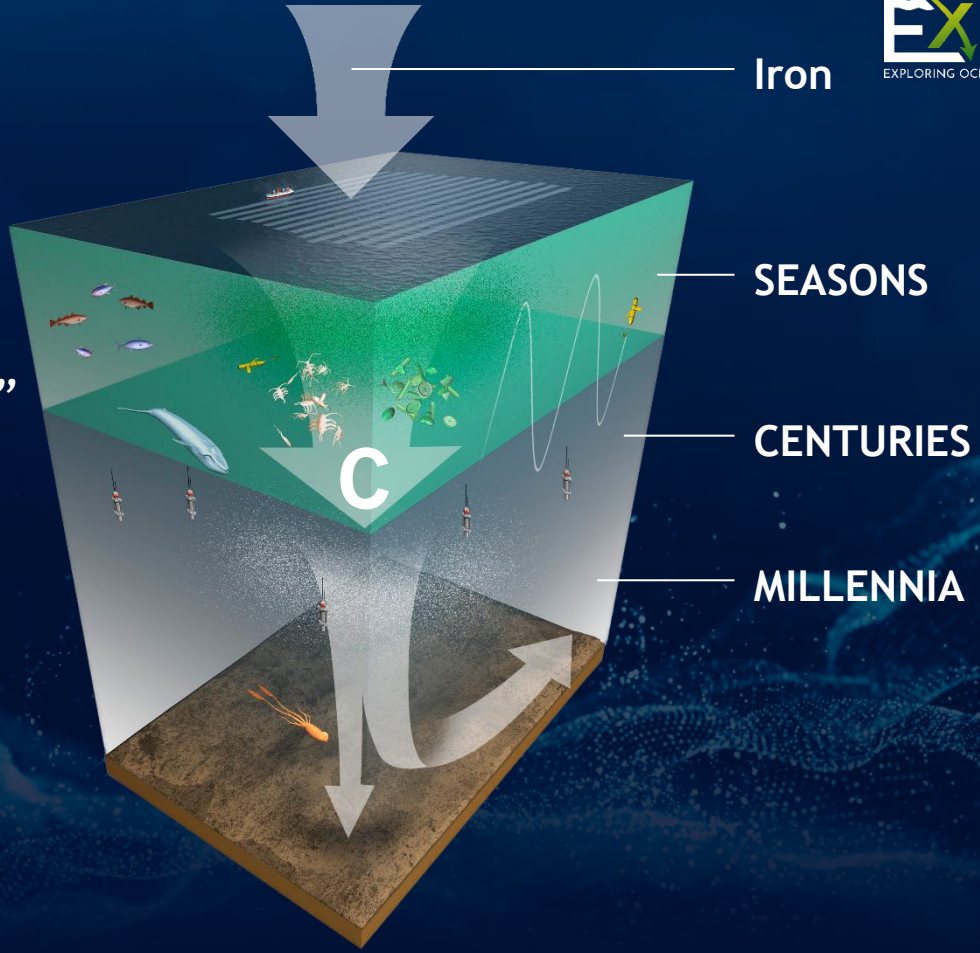




1.3 tonnes Fe added
4000 tonnes $CO_{2\text{-eq}}$ removed

How much carbon gets deep?

- ✓ Transport of carbon via *"Biological Carbon Pump"*
- ✓ Key questions in next generation studies are additionality and durability



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Why is ocean iron worth considering for mCDR?

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- ✓ **Scaling**
  >1-2 Gt CO_2/y considering only high nutrient areas
- ✓ **A little iron goes a long way**
  1 : 1000 iron:carbon ratio from (inefficient) field experiments
- ✓ **Cost**
  <$50 tonne CO_2 -lower than any other marine CDR approach
- ✓ **Experience**
  13 field experiments; no observed harm & 4,000 tonnes $CO_{2\text{-}eq}$ removed

What potential risks need further consideration?

- before ocean iron is deployed at scale

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✓ **Deoxygenation**

Mid-water decreases - at Gt scale- see Oschlies et al. 2010, 2025
- at pilot scale- much smaller

✓ Downstream impacts

Nutrient robbing - at scale impacts accompany large CO_2 removal
- biological carbon pump efficiencies hard to predict

✓ **Harmful algal blooms**

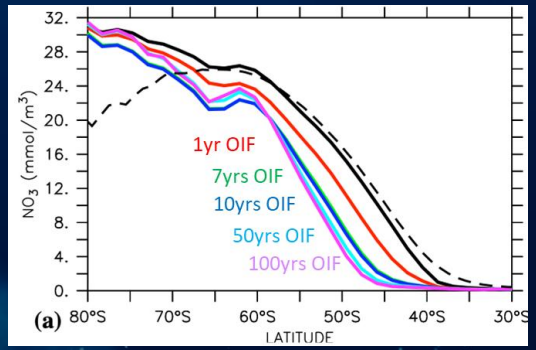
Pseudonitszchia diatoms w/ domoic acid- not higher in OIF field studies

✓ **Other greenhouse gases**

Prior studies encouraging- offset <10%, but can't ignore (N_2O, CH_4, DMS)

Models are needed to predict potential impacts at scale

Impacts on surface NO_3 in response to 2x increase primary production



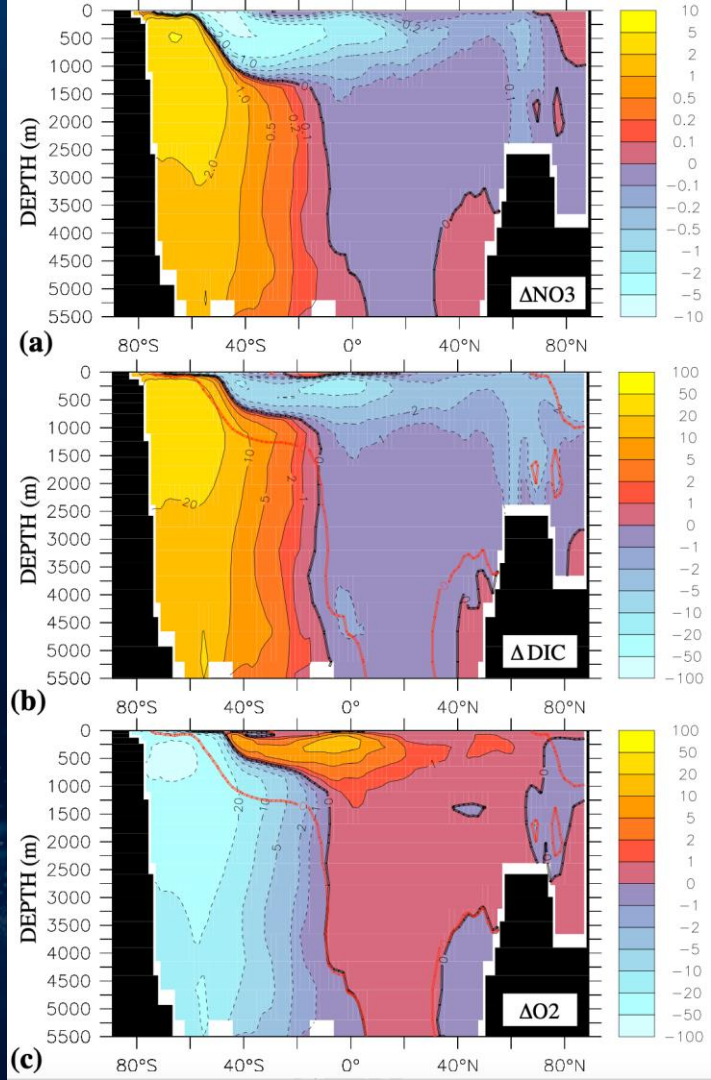
Surface NO_3 <1-5 mmol m^{-3} decrease in SO

Deep DIC <1-10 mmol m^{-3} increase in SO ≈2300 mmol m^{-3} bkg

O_2 ≈3% global decease, but increase O_2 in OMZ's

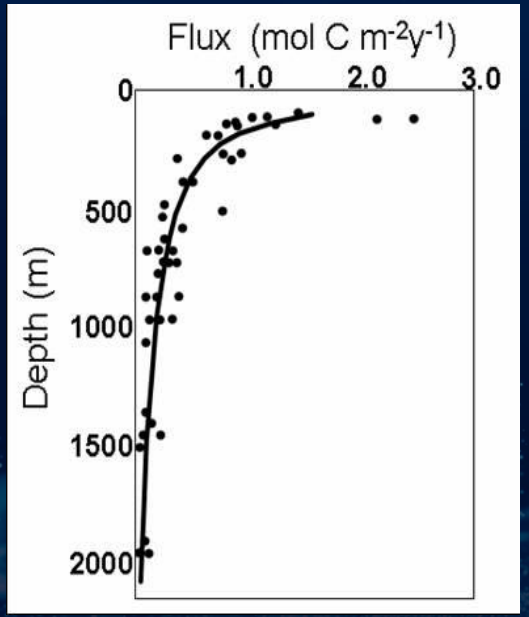
"Southern Ocean waters remain well oxygenated even under large-scale simulated OIF on centennial time scales."

A. Oschlies, W. Koeve, W. Rickels, K. Rehdanz, 2010

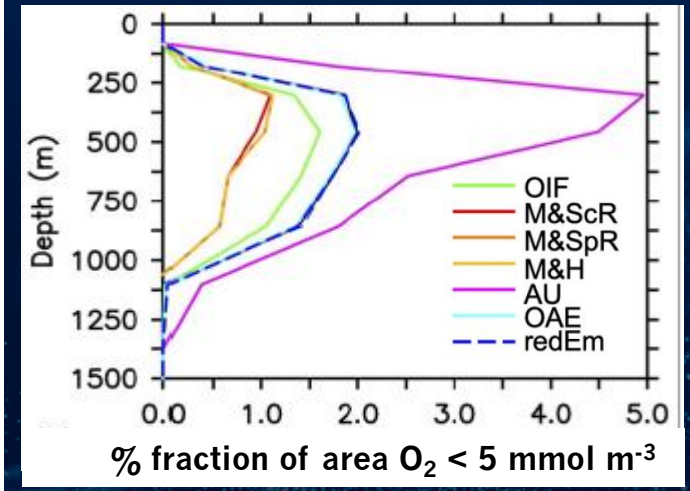


Subsurface impacts depend on remineralization curve for sinking particles via biological carbon pump

- ✓ impacts O_2, N_2O, CH_4, pH/DIC deep
- ✓ not the same for C, N, P, bSi, Fe
- ✓ impacts downstream
  - nutrient “robbing”
- ✓ impacts durability and additionality



J. Martin, G. Knauer, D. Karl, W. Broenkow. 1987



A. Oschlies, C. Slomp, A. Altieri, N. Gallo, M. Gregoire, K. Isensee, L. Levin, J. Wu, 2025

For mCDR to “work” there must be change

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<u>If current trends continue-</u>
elevated temperatures, sea level rise, ocean acidification, deoxygenation, ocean heat waves, & on land- environmental, crop & human losses…

For mCDR to “work” there must be change

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Oschlies et al. 2025*

OIF removes 200 Gt $CO_{2\text{-eq}}$ over 100 yrs

- decease global O_2 on average 3%
- increase suboxic area <1%
- decrease suboxic area off So. America

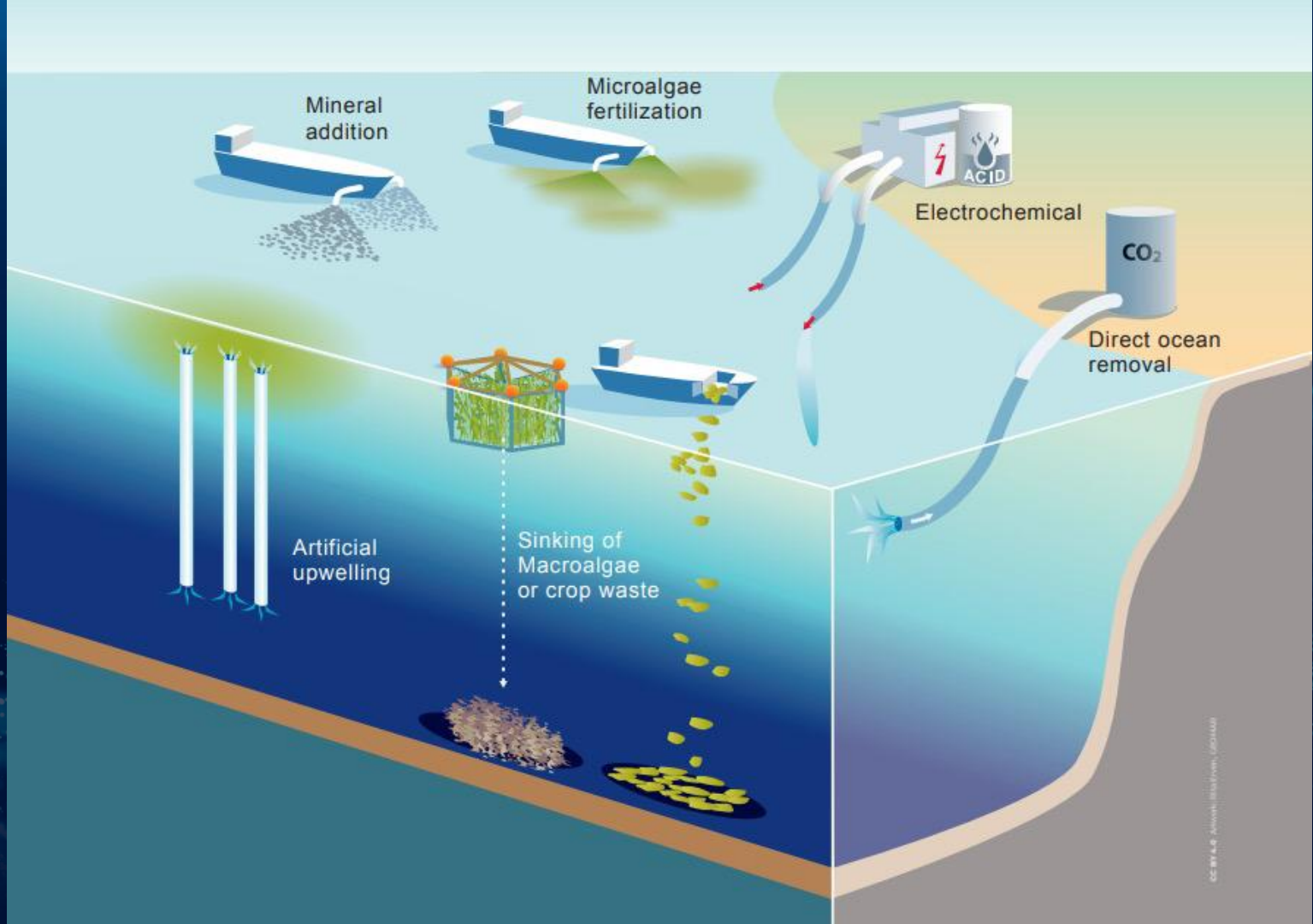
A. Tagliabue, B. Twining, N. Barrier, O. Maury, M. Berger, L. Bopp, 2023

OIF removes 150 Gt $CO_{2\text{-eq}}$ by 2100

- decrease O_2 <1% (suppl. Fig. 3)
- 5% additional biomass decrease off So. America

* 220-660 Gt $CO_{2\text{-eq}}$ required to meet climate targets

All forms of mCDR will have impacts



Will need to consider all aspects when deciding if, when, how much mCDR is wise/responsible

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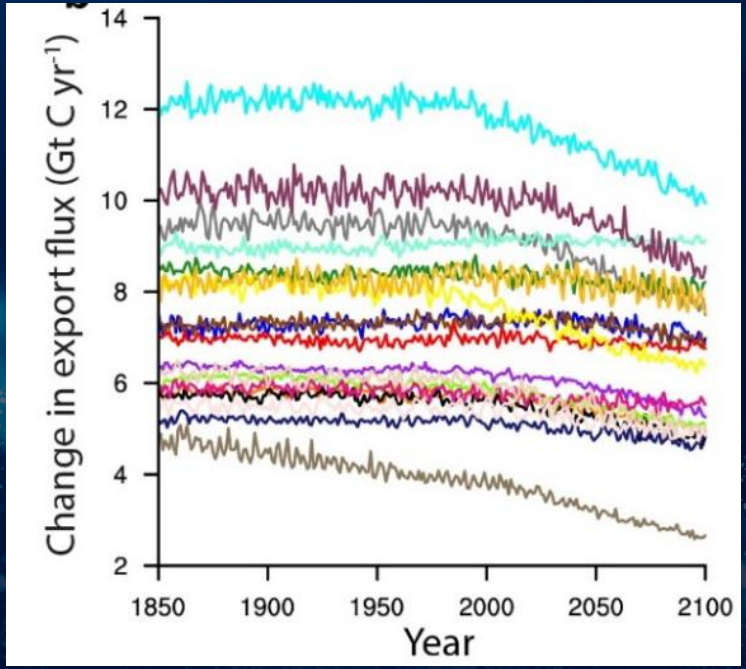
C. Vivian, M. Boettcher, M. Elliot, N. Mengis, C. Merk, A. Oschlies, P. Boyd, A. Lancaster, O. Corry, M. Sugiyama, A. Gupta, 2025

	Enhancing of the biological carbon pump			Enhancing the chemical carbon sink		
	Microalgae fertilization	Sinking of Macroalgae or Crop Waste	Artificial upwelling	Mineral addition	Electrochemical	Direct ocean removal
Durability of carbon storage	10s – 1000s	100s – 1000s	10s – 100s	10,000+	10,000+	10,000+
Energy demand [1]	⚡	⚡–⚡⚡	⚡	⚡⚡–⚡⚡	⚡⚡	⚡⚡
Knowlegde gaps [2]	?	??	??	??	??–??	???
Technical readiness [3]	Medium - high	Medium	Low	Medium	Low	Low
	Occurrence and extent of impacts depends on where, how much, and how the methods are used.					
Marine ecosystems & biodiversity	🟡🟡	🟡🟢	🟡🟡🟡	🟡🟢	⚫	🟡
Ocean acidification	⚫	⚫🟡	⚫	🟢	🟢	🟢
Area use conflicts [4]	⚫	🟡🟡	🟡🟡🟡	🟡⚫	⚫	⚫

[1] Can include production and transportation
[2] Based on peer-reviewed research and reflecting uncertainties
[3] For implementation at scale
[4] On land and at sea

⚫ No effect 🟢 Potentially positive effects 🟡 Potentially negative effects

mCDR approaches that rely on the biological carbon pump are hard to assess with current models



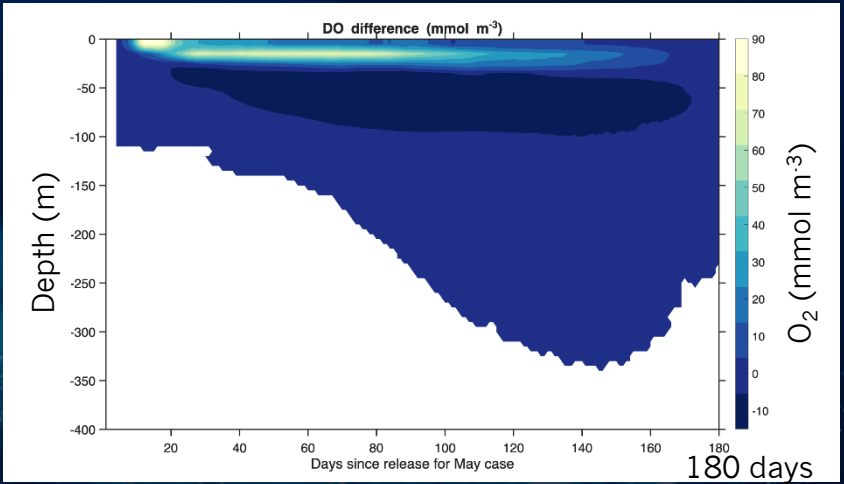
Predictions from 19 coupled climate models

"there are 12 processes that are likely to have the greatest impact on present-day and future projections of export flux, of which 10 are currently missing from the majority of climate models."

S. Henson, C. Laufkotter, S. Leung, S. Giering, H. Palevsky, E. Cavan, 2022

Remember that impacts at Gt scale are many thousands of times greater than at pilot scales

Difference (in vs out) in O_2 vs time
Model OIF expt. NE Pacific

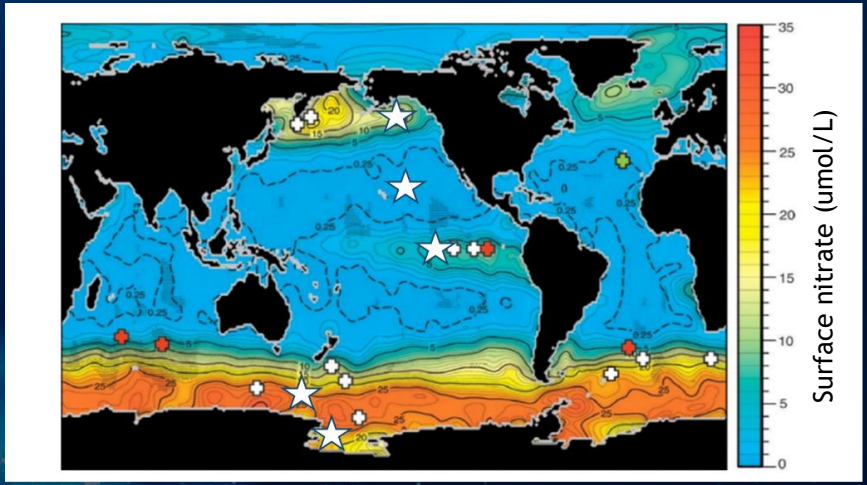


Model OIF field experiment NE Pacific
Xiu, Chai et al unpub.

"Need observational studies to make models as accurate as possible"

A. Watson, P. Boyd, S. Turner, T. Jickells, P. Liss, 2008

The case for field studies



★ Proposed sites for next generation field studies

ExOIS Buesseler & 22 co-authors Frontiers, 2024

"There is consensus within the scientific community that none of the iron fertilization field experiments conducted to date could have caused longterm alteration of ocean ecosystems."

P. Williamson, D. Wallace, C. Law, P. Boyd, Y. Collos, P. Croot, K. Denman, U. Riebessel, S. Takeda, C. Vivian, 2012

Conclusions

1. All mCDR approaches will have impacts
2. These will include changes to geochemistry (incl. O_2) and ecology, and hopefully decreasing atmospheric CO_2
3. Science is incomplete to predict large scale impacts
4. Models alone are lacking in key BCP processes
5. Field studies needed to inform models
6. Impacts at field scale are small/temporary (OIF)

We need – along with fossil fuel reductions -
to consider multiple CDR approaches

Time to work together
& move ahead with responsible research