UC SANTA BARBARA

Evaluating the potential for net-negative CO_2 removal via biomass storage in anoxic marine basins

Earth and Planetary Sciences, ETH Zürich

October 29, 2024

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Outline

Part I: The Current State of Marine CO_2 Removal

Part II: A research framework to enable model development and decision-making

- Biomass deployment phases and key processes
- Observational scales and strategies

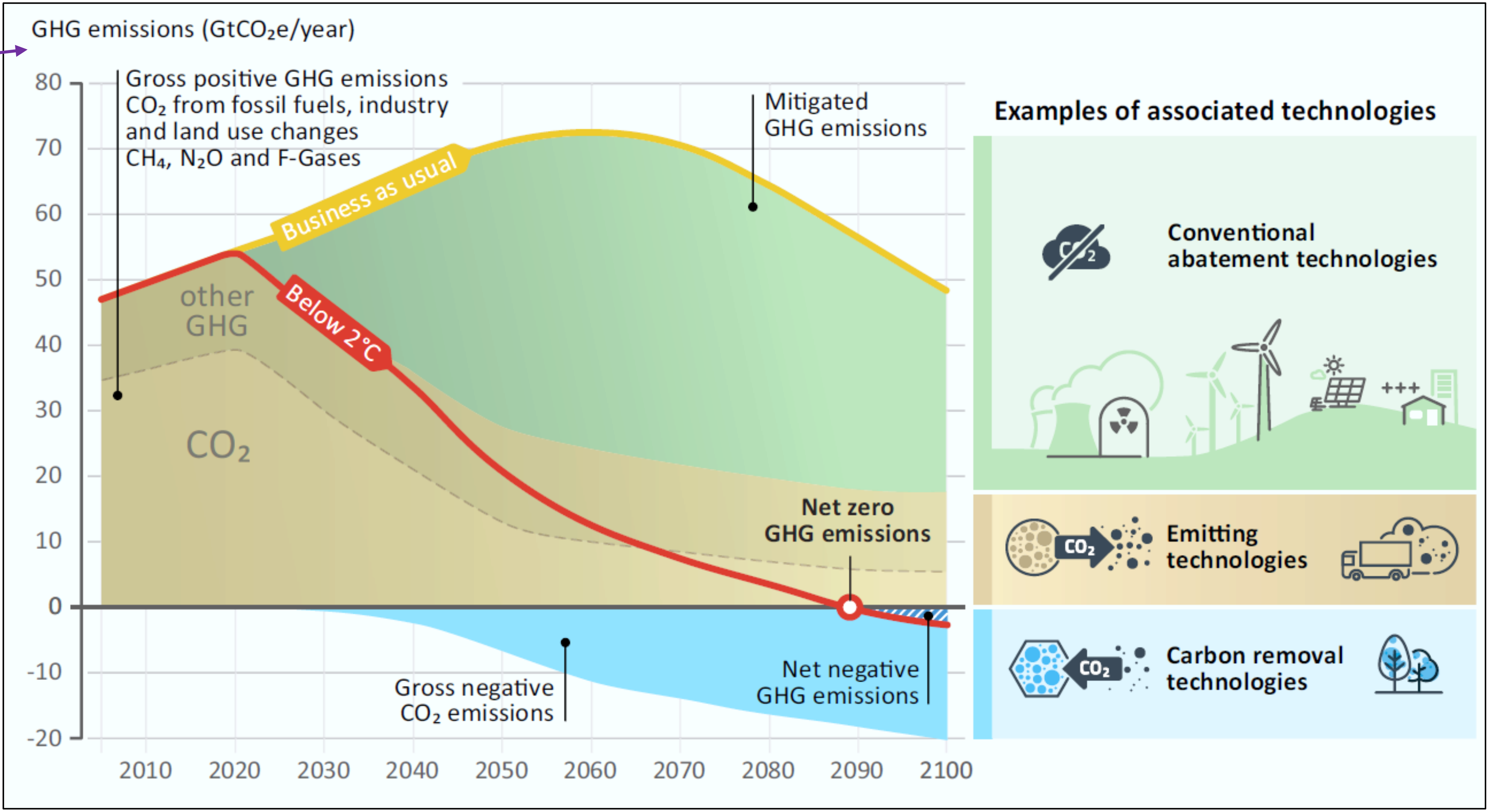
Part III: Initial results from field tests and lab experiments

- What is the fate of biomass C placed in an anoxic, hypersaline brine?
- How would this addition impact the environment?

Orca Basin, Gulf of Mexico, July 2023

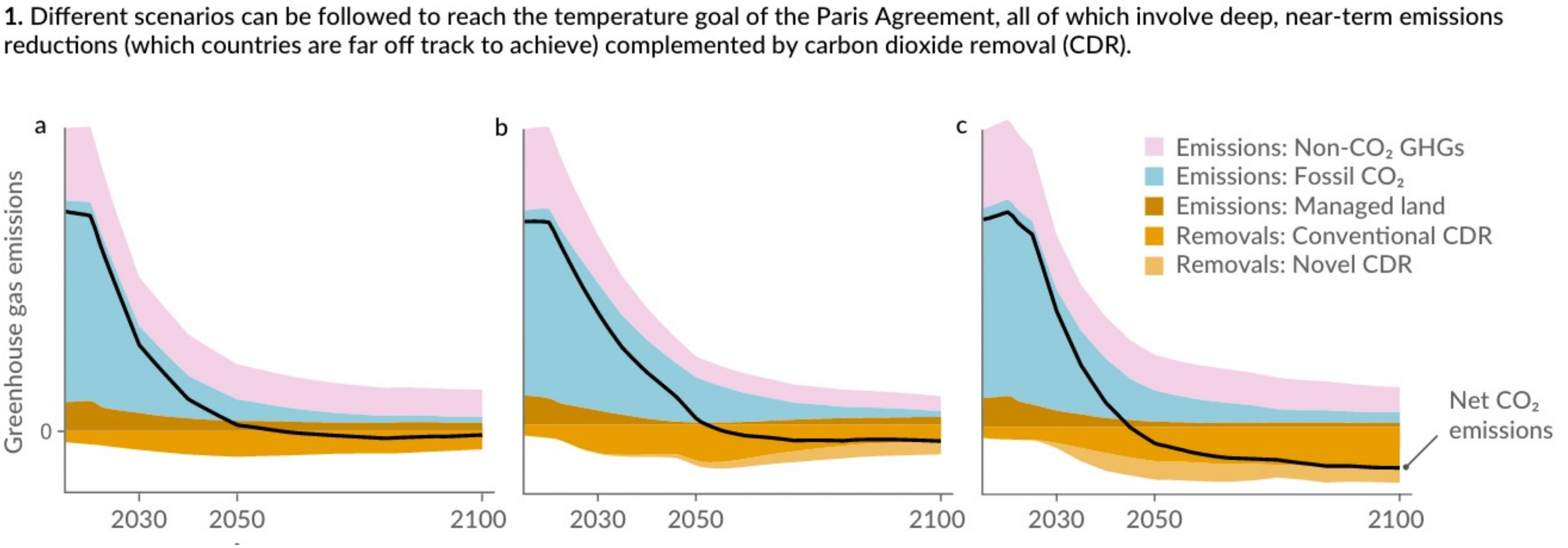
Why are we talking about net-negative CO_2 removal (CDR)? CDR is now required to meet climate targets

"billion tonnes of atmospheric CO_2 equivalent" (also 10^{15} g= Pg)



Emissions reductions are essential but insufficient.

Net-negative CO_2 removal (CDR) is required to meet climate targets



Conventional CDR = forestry, mostly

- currently achieves ~2 Gt CO_2e / yr
- durability unclear (e.g., wildfire)

The amount of CDR needed will directly depend on real emissions reductions and other feedbacks.

Novel CDR strategies leverage natural feedbacks across the Earth system

Analogs for these processes and their climate impacts exist in the geologic record.

	Inorganic	Organic
Terrestrial	Enhanced Rock Weathering	Biochar
Marine	Alkalinity Enhancement Direct Ocean Removal	Biomass Sequestration

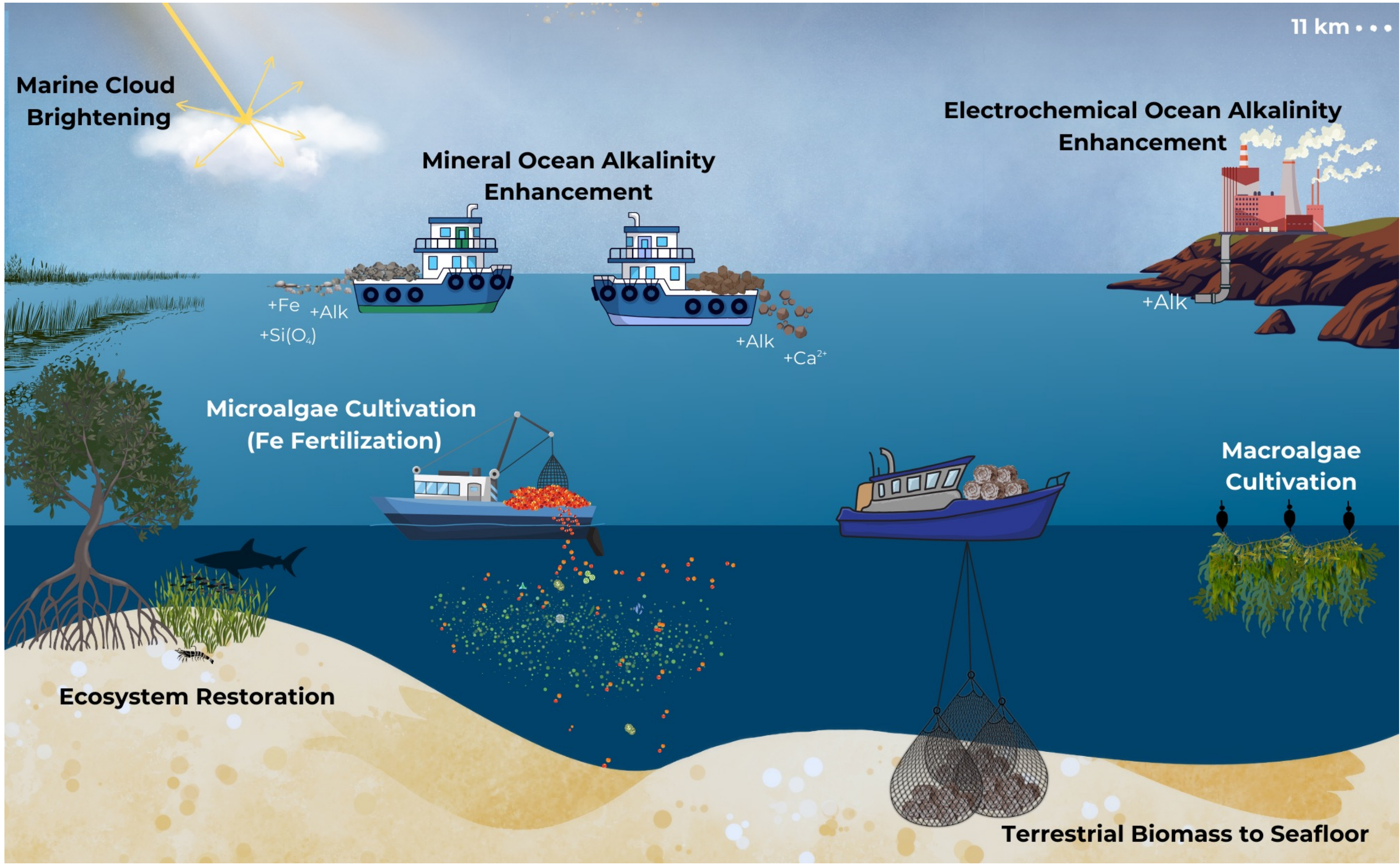
Novel CDR strategies involving the deep ocean

Examples:

- Ocean alkalinity enhancement
- Electrochemical techniques

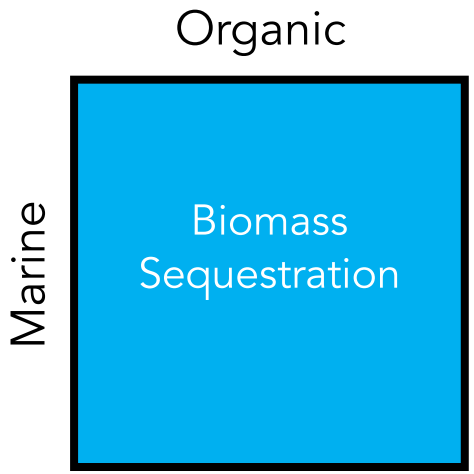
- Nutrient fertilization
- Artificial upwelling / downwelling
- Seaweed cultivation (macroalgae)
- Terrestrial biomass sequestration

	Inorganic	Organic
Marine	Alkalinity Enhancement Direct Ocean Removal	Biomass Sequestration



Roberts et al., in prep

Biomass-based marine CDR: Challenges and advantages



"Open system" issues (often shared with inorganic methods)

- Crosses jurisdictional boundaries
- Mobile, dilute signals (challenging to monitor)
- Overlapping impacts (challenging to attribute)

Biomass is a complex feedstock

- Heterogeneous composition by species, season, age
- Dynamic interactions with marine biogeochemistry
- Competing uses

Key advantage:

- Photosynthesis! Does not compete for the green energy grid

Biomass sources for marine CO_2 removal

Different materials will have very different fates in the environment.
Marine sources require cultivation.

CO_2 (atm)

⇩

Biomass C

⇩

Biomass C +
Dissolved organic C (DOC) +
Dissolved inorganic C (DIC) +
methane (CH_4)

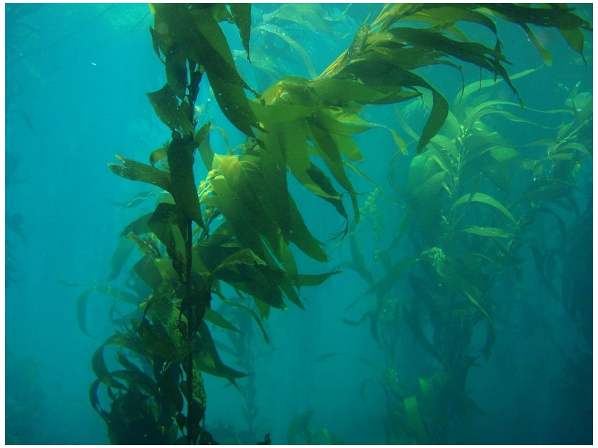
⇩

CO_{2}(atm)?

* Leverage existing material and infrastructure
* Initial LCA is >90% CO_2 efficient

Crop waste (e.g. sugarcane bagasse)

Macrocystis (kelp)



Credit: Claire Fackler, via ccgproject.org

Sargassum *BBC*

Carboniferous

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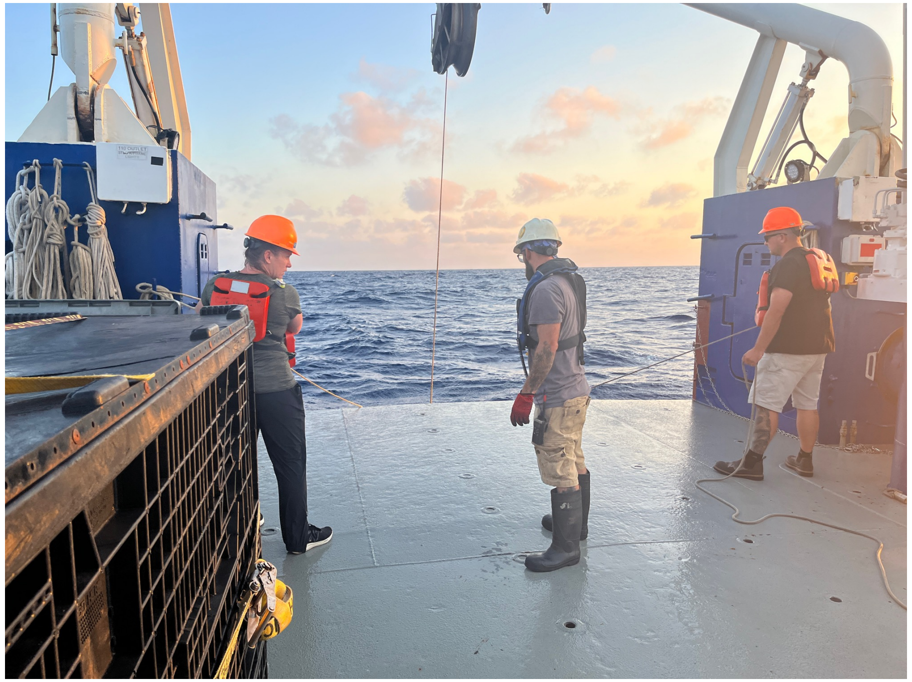


Orca Basin, Gulf of Mexico, July 2023

Generalizable phases of biomass-based mCDR

Field trials and potential deployments for biomass mCDR require regulatory and verification structures that can be enforced across very different specific proposals.

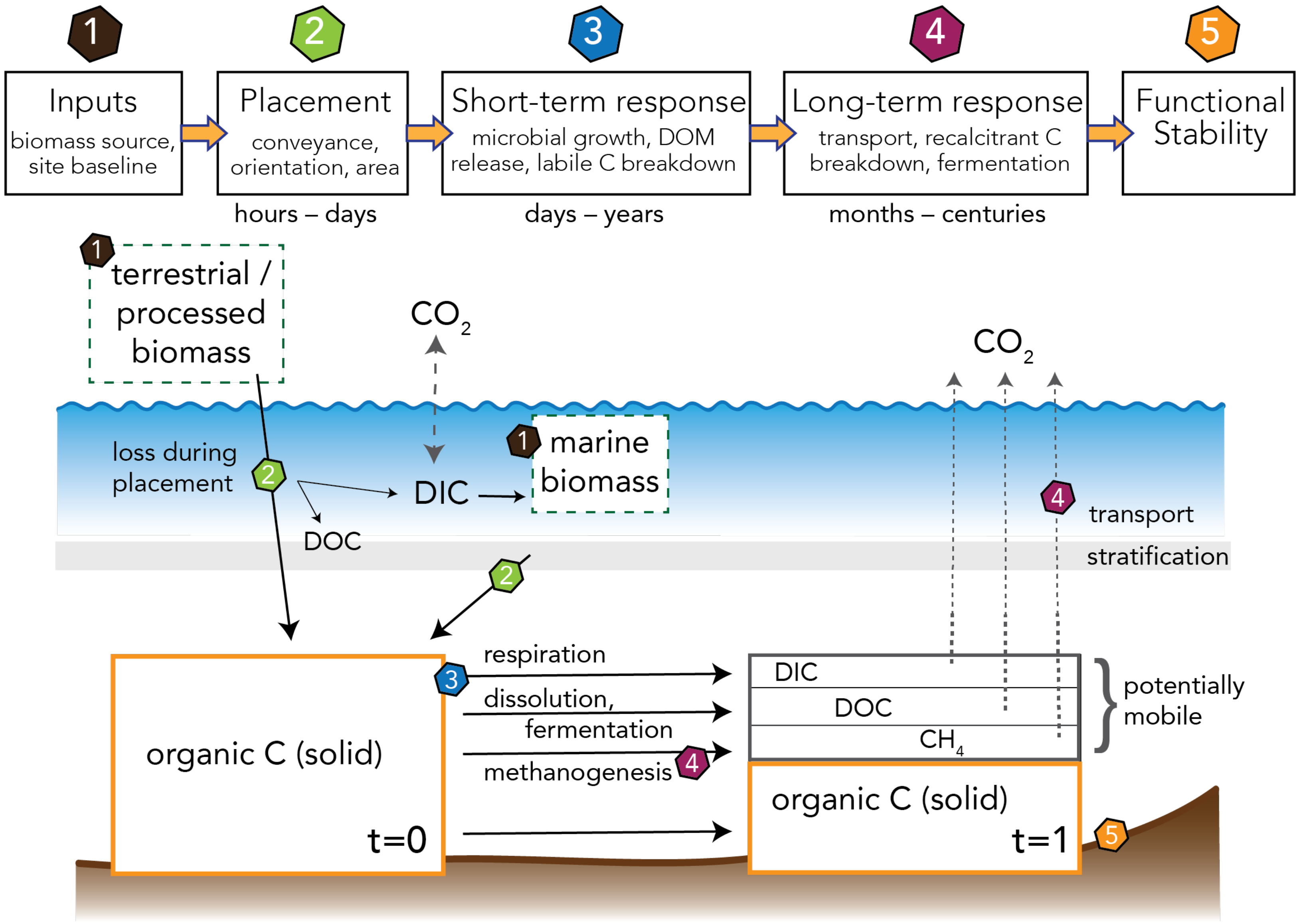
Phases are designed to be generalizable and pathway-agnostic.

biomass source

labile ⟺ recalcitrant

sequestration site

open ⟺ closed system

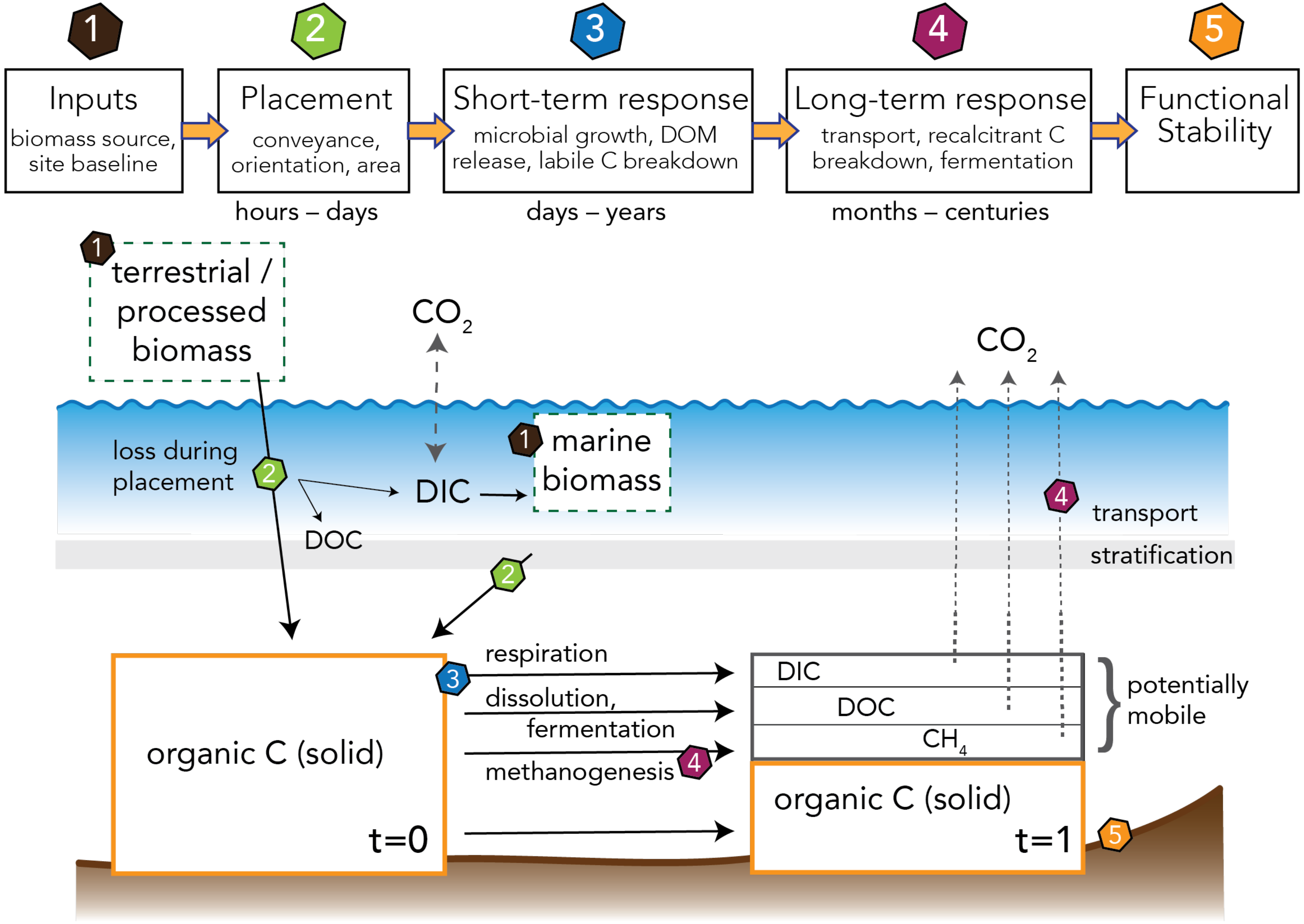


Generalizable phases of biomass-based mCDR

This includes long-term processes.

Functional stability is defined as a final state of the carbon system perturbation that can be described with high confidence.

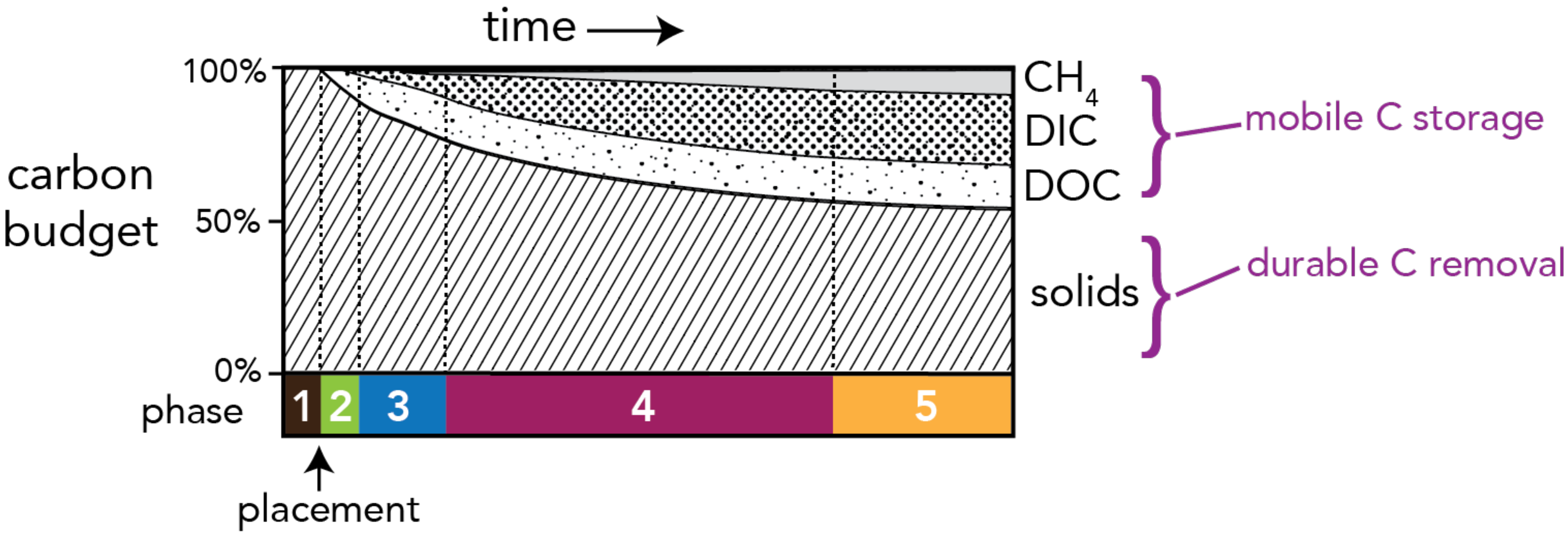
Biomass solids are either
- exhausted (transferred to mobile C)
- highly recalcitrant (ongoing reactivity approaches zero)



Tracking the fate of biomass carbon over time

Solid organic C can be converted to:

DOC	solubilization
DIC	respiration, fermentation
CH_4	methanogenesis
(POC)	solid breakdown



Generalizable phases of biomass-based mCDR

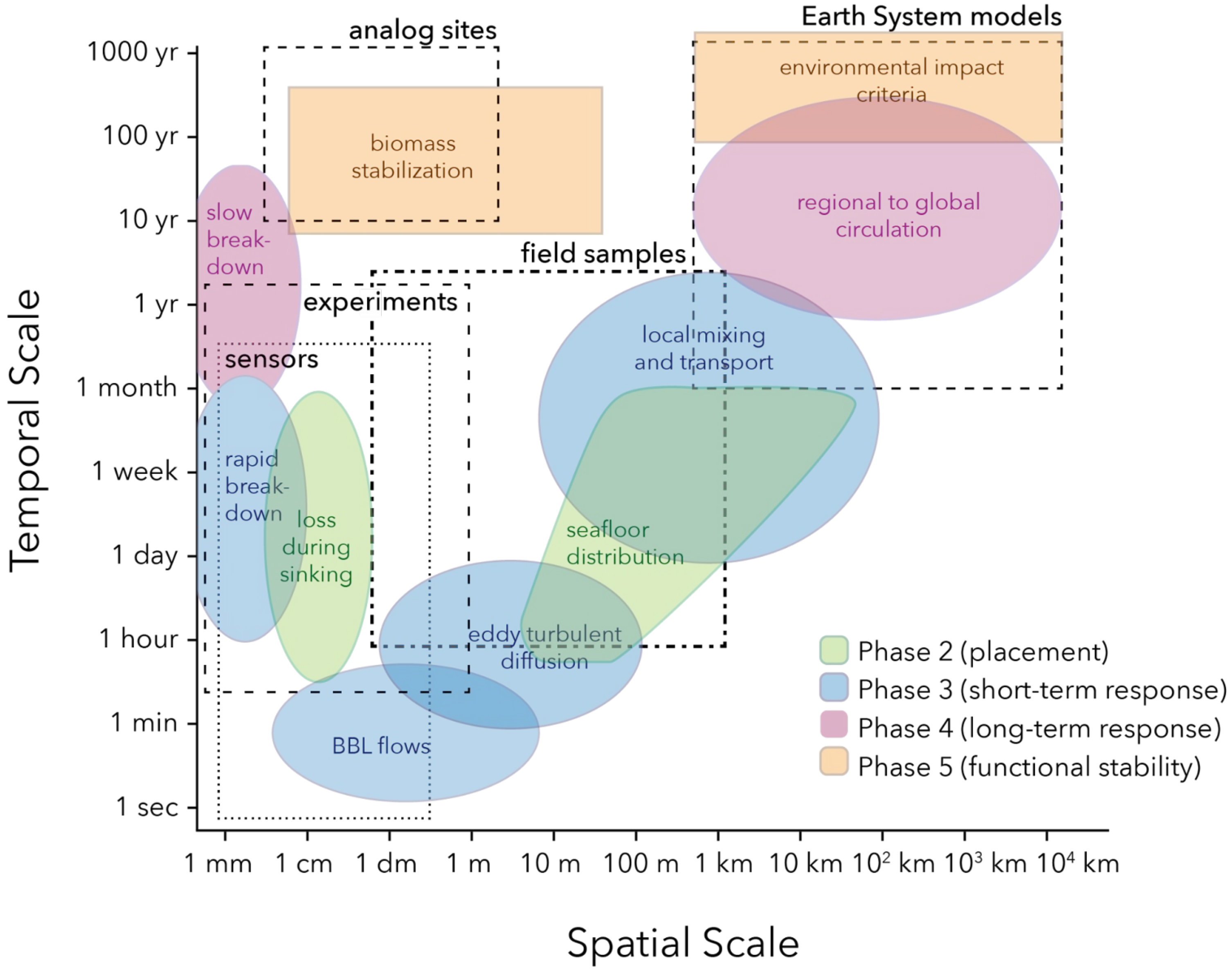
A wide range of processes impact durable carbon storage and environmental outcomes.

These processes span vast scales:

- seconds to millennia
- microns to kilometers

To gain meaningful information about these phenomena,

we need observational strategies that target the right spatial and temporal scales!



Aligning scales: observational strategies and research objectives

- Monitoring, Reporting, and Verification (MRV) structures
- Framework to assess and compare strategies

Phase	Research Objective	Field Data	Analog Sites	Experiments	Models
	E.g.:	seawater samples, sensors	aged organics, paleo-records	lab + in-situ bottle incubations	circulation, multi-G kinetics
1: Inputs					
	Biomass source composition and embedded impacts	<external modules>			
	Sequestration site baseline				
2: Placement					
	Loss of biomass during sinking				
	Distribution of biomass solids on the seafloor				
3: Short-term response					
	Biomass colonization and community growth				
	Biomass breakdown rates and pathways				
	Rates and products of DOM release				
	Transport and mixing				
4: Long-term response					
	Breakdown rates and pathways over time				
	Transport, mixing, and atmospheric interaction				
5: Functional stability					
	Biomass condition				
	Net carbon stored over a target timescale				

Raven et al., under review @ERL

Part 3: Initial Results: Ocean Carbon Retention under Anoxia (OCRA)

* How is biomass transformed, degraded or preserved in anoxic brine?

Part 3: Initial Results: Ocean Carbon Retention under Anoxia (OCRA)

2023-2024

investment funding

coordinated grant funding:
Grantham Foundation

Carboniferous

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LSU Center for Energy Studies

SCRIPPS INSTITUTION OF OCEANOGRAPHY

RUTGERS

Orca Basin 2023-2024
CRA
Ocean Carbon Retention under Anoxia
NOISE Lab @ UCSB

Approach: store crop wastes in anoxic (hypersaline) marine basins

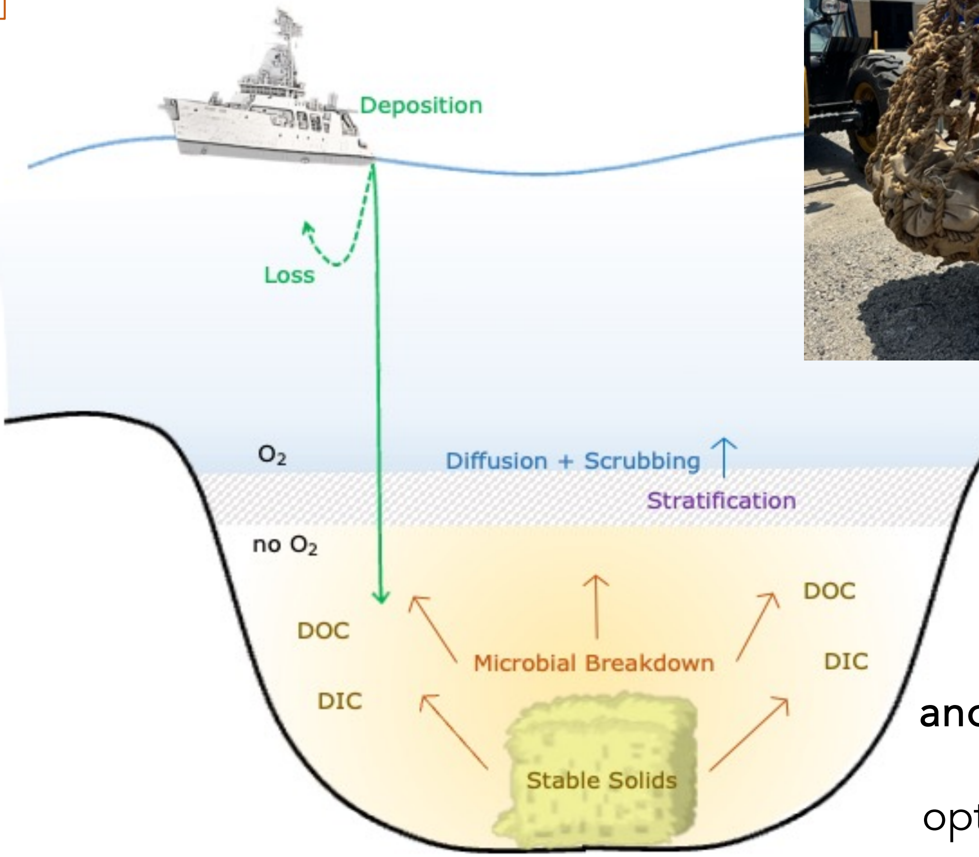
Crop waste
(e.g. sugarcane bagasse)

densification

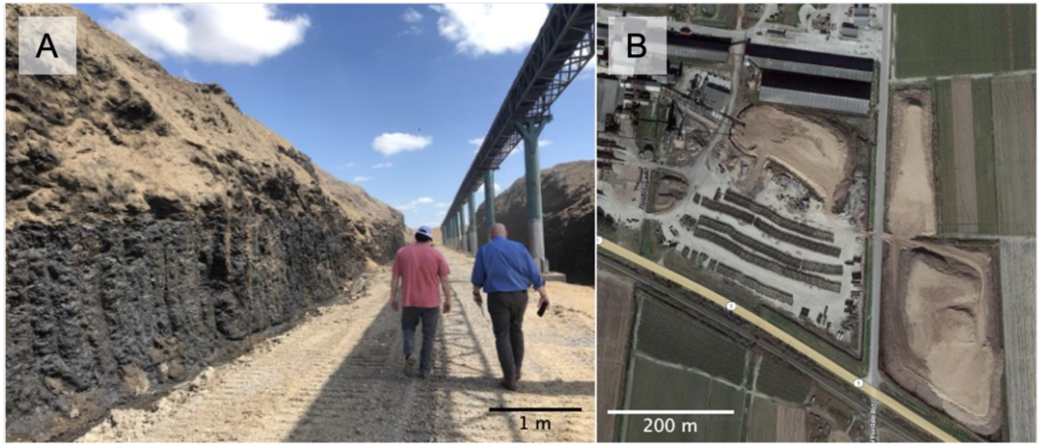
packaging
(burlap, jute, sampling gear)

placement on seafloor
(in brine pool)

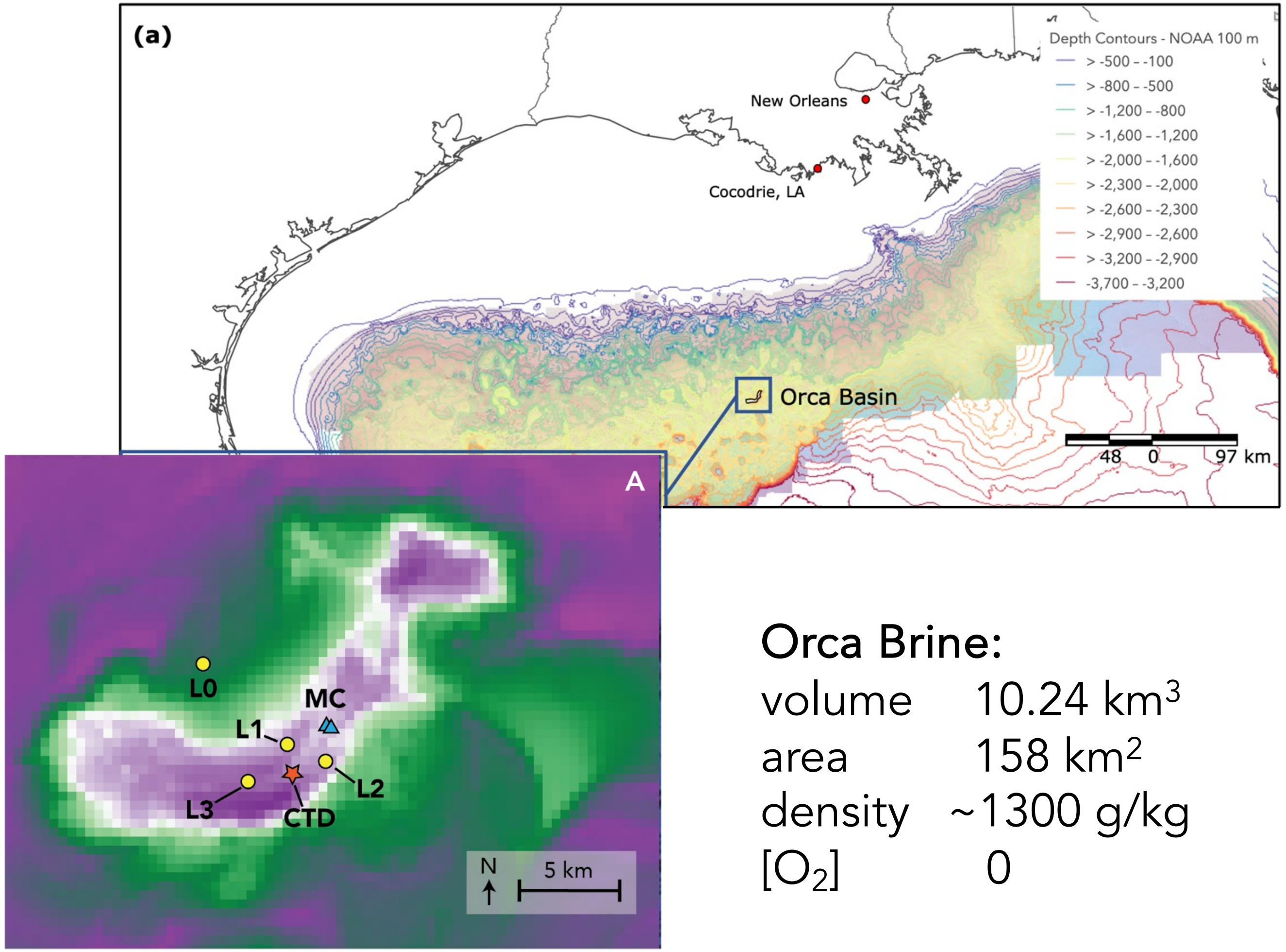
counterfactual
burned, stored in tended piles, methane emissions



anoxic brine pool
no animals,
optimizes storage

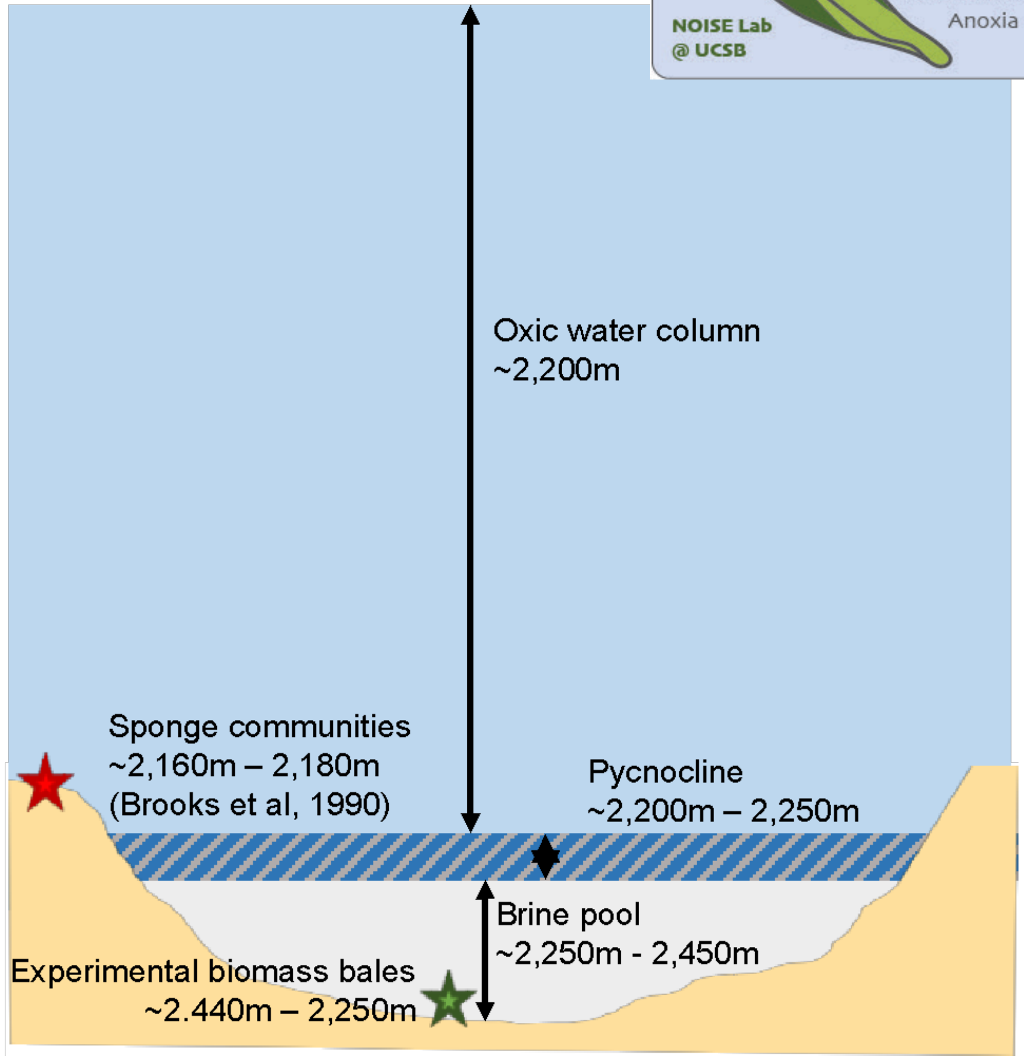


Field Site: Orca Basin, Gulf of Mexico



Orca Brine:

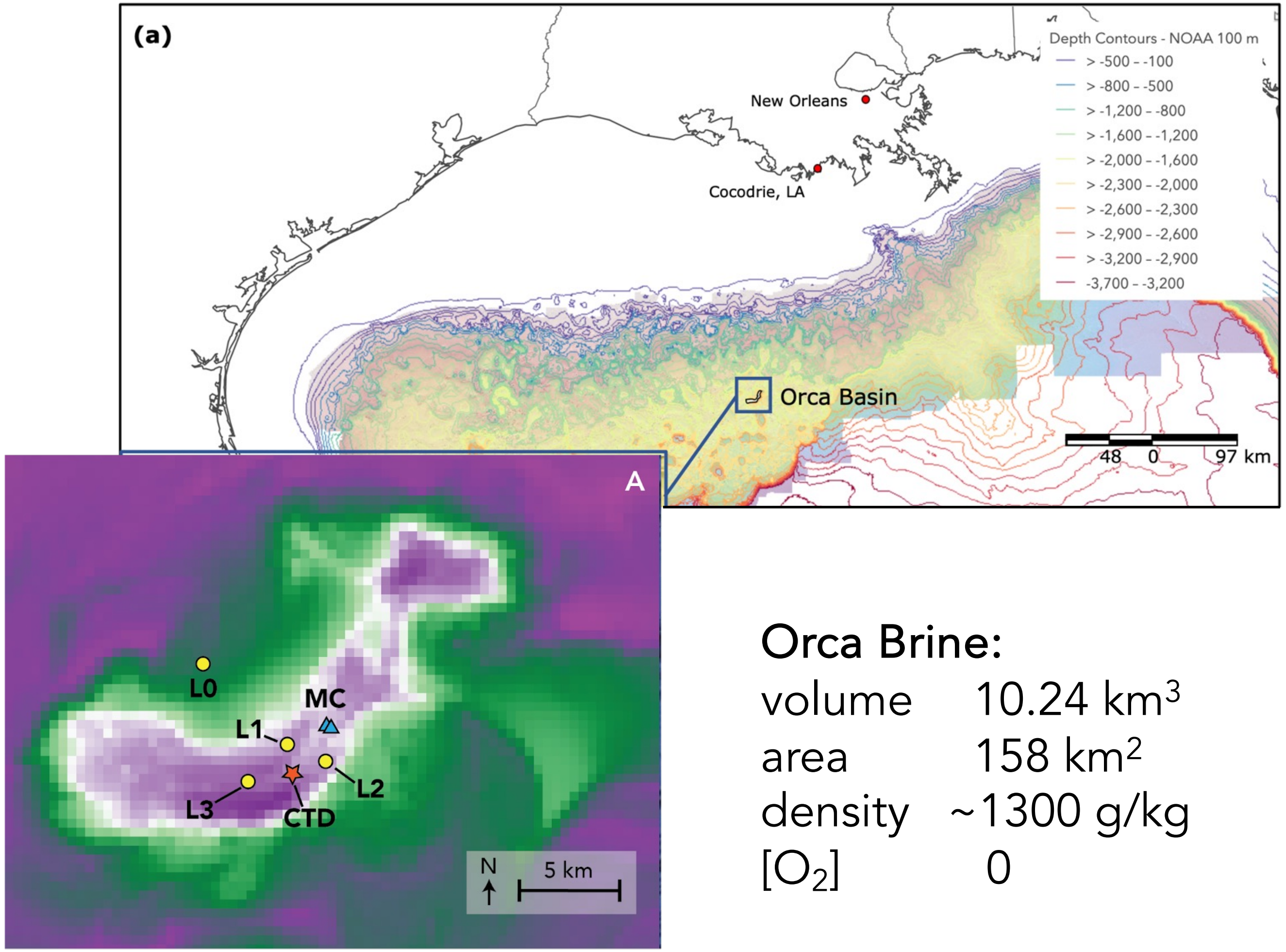
volume	10.24 km^3
area	158 km^2
density	~1300 g/kg
$[O_2]$	0



data: Diercks et al., 2019

OCRA cruise report: https://github.com/UCSB-NOISELab/OCRA/

Field Site: Orca Basin, Gulf of Mexico



Orca Brine:

volume 10.24 km^3
area 158 km^2
density ~1300 g/kg
$[O_2]$ 0

Physical volume

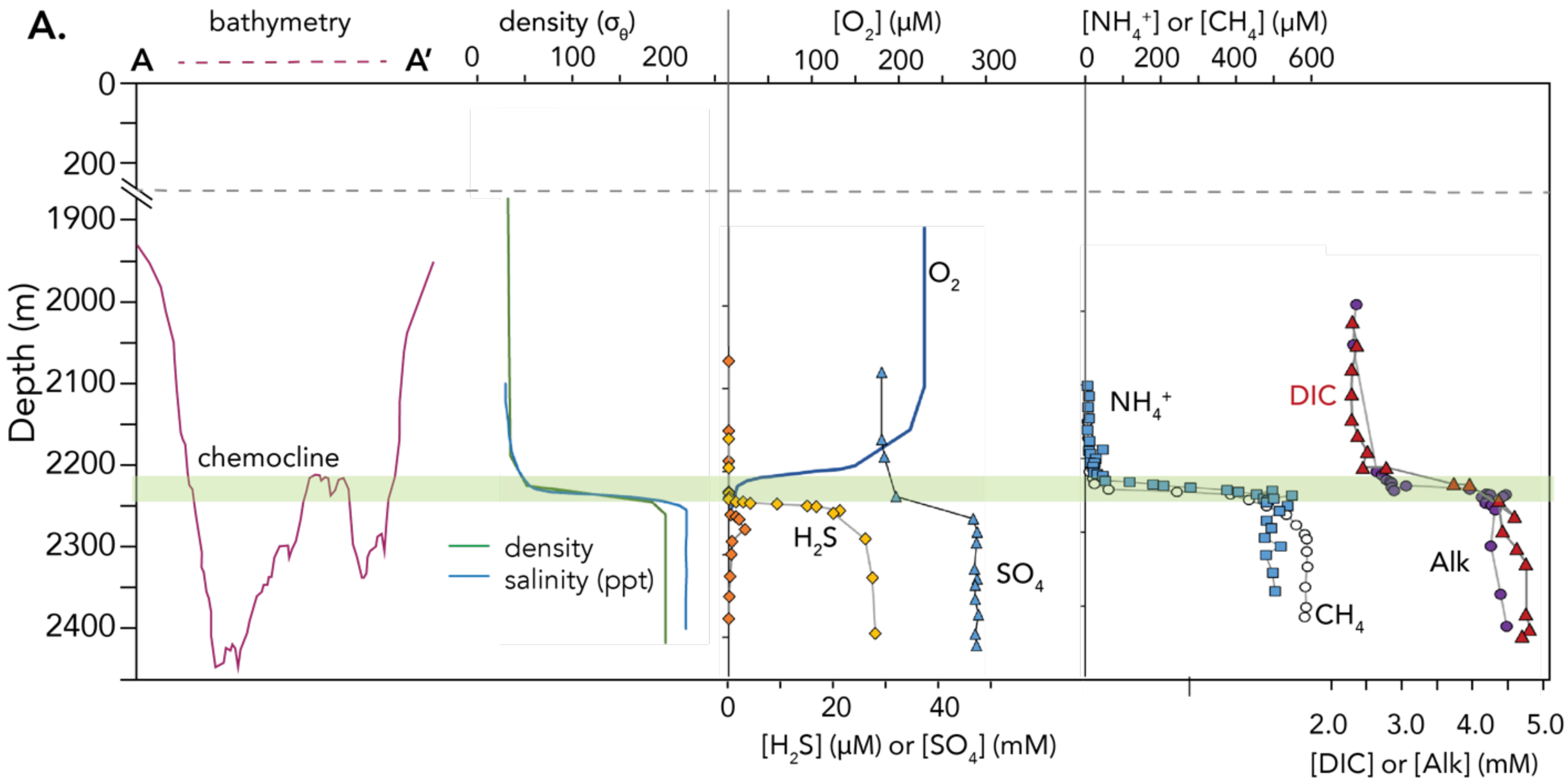
100% of brine area x 4-m-thick layer

~200 Mt CO_2e as solid biomass

data: Diercks et al., 2019

OCRA cruise report: https://github.com/UCSB-NOISELab/OCRA/

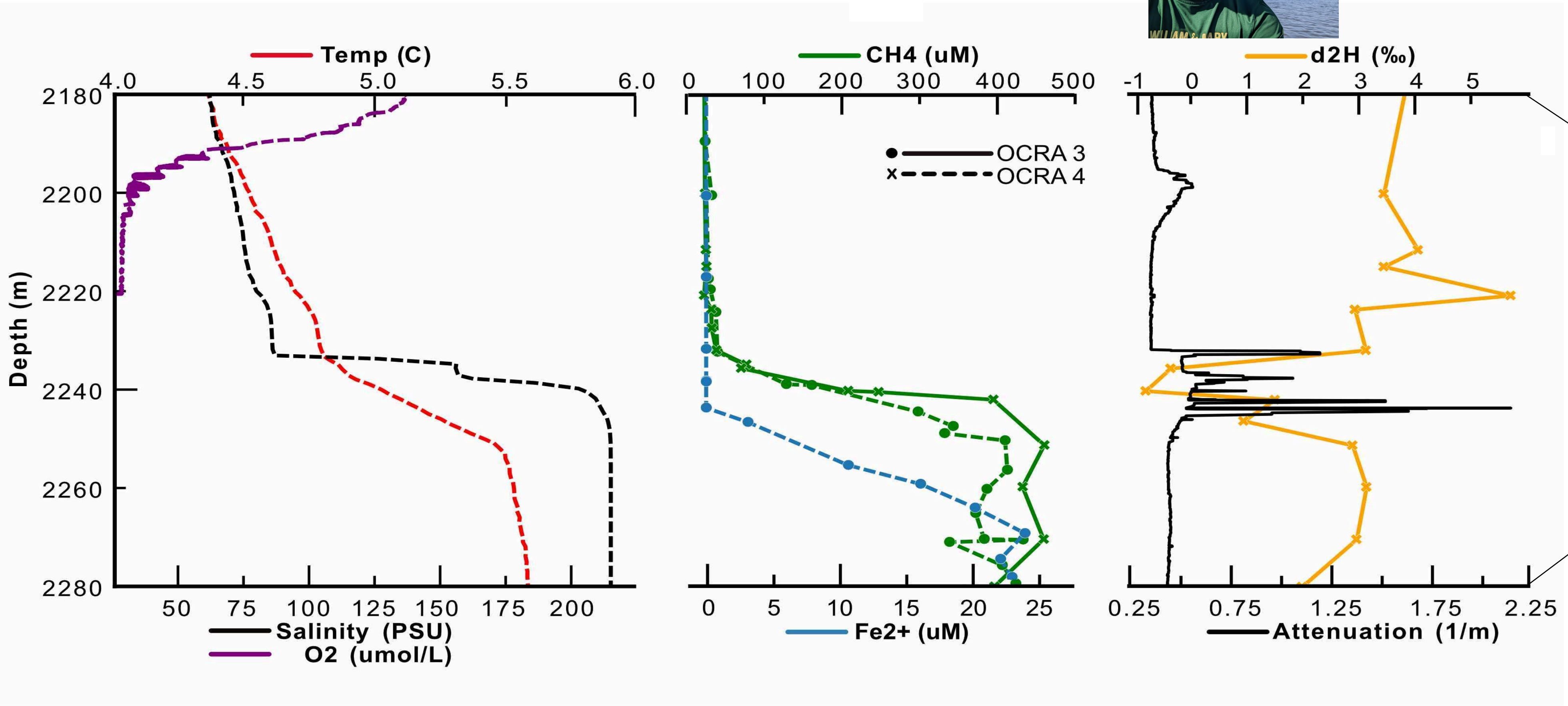
Orca Basin is isolated from overlying seawater by a density interface

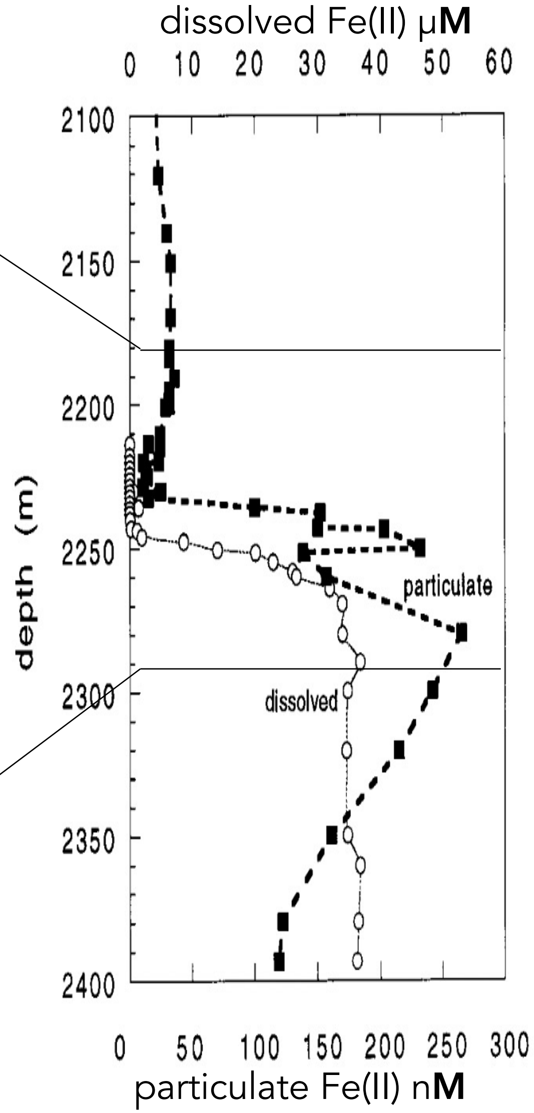


Orca brine accumulates:

- Salt (NaCl)
- OM breakdown products (DOC, DIC, nutrients)
- Sediment-sourced methane

(More fun biogeochemistry at the pycnocline…)





- Particles float at the interface and degrade there before sinking further.
- ^{2}H-depleted water trapped at this density horizon: Fe / Mn oxide cycling?

Evans, Martinez, and Raven, in prep

Van Cappellen et al.,1998

Observational Strategy: Terrestrial Biomass Storage in Orca Basin

Phase	Research Objective	Field Data	Analog Sites	Experiments	Models
	E.g.:	seawater samples, sensors	aged organics, paleo-records	lab + in-situ bottle incubations	circulation, multi-G kinetics
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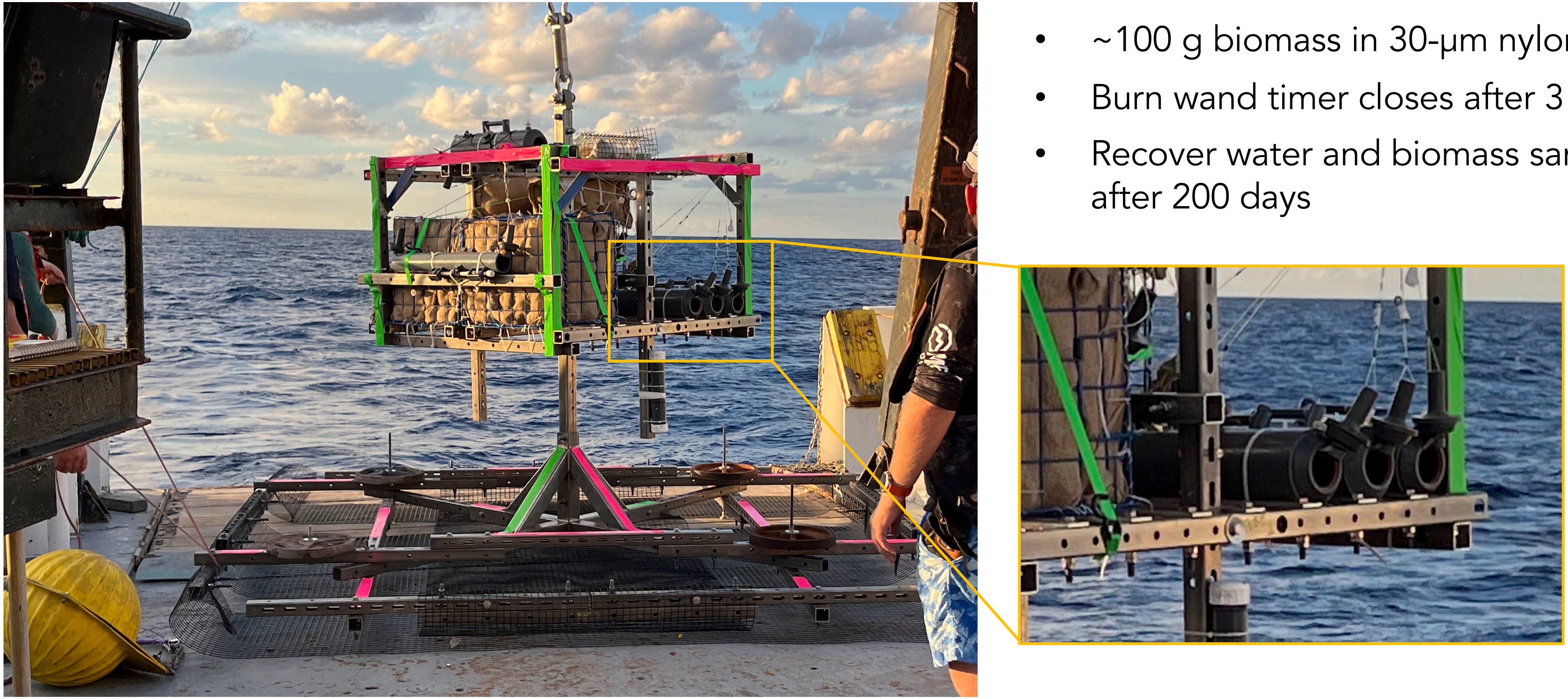
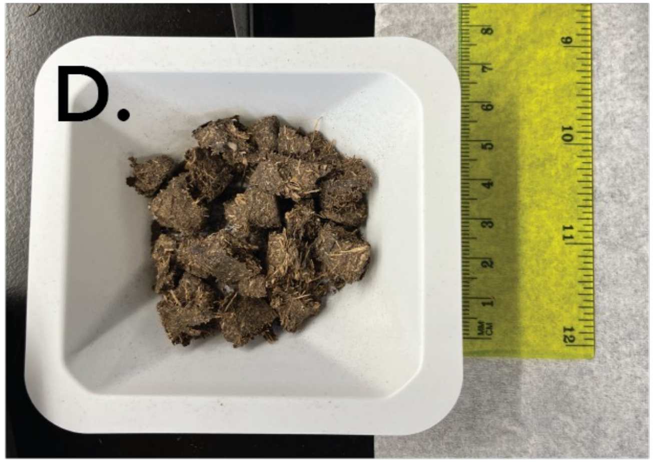
Raven et al., under review @ERL

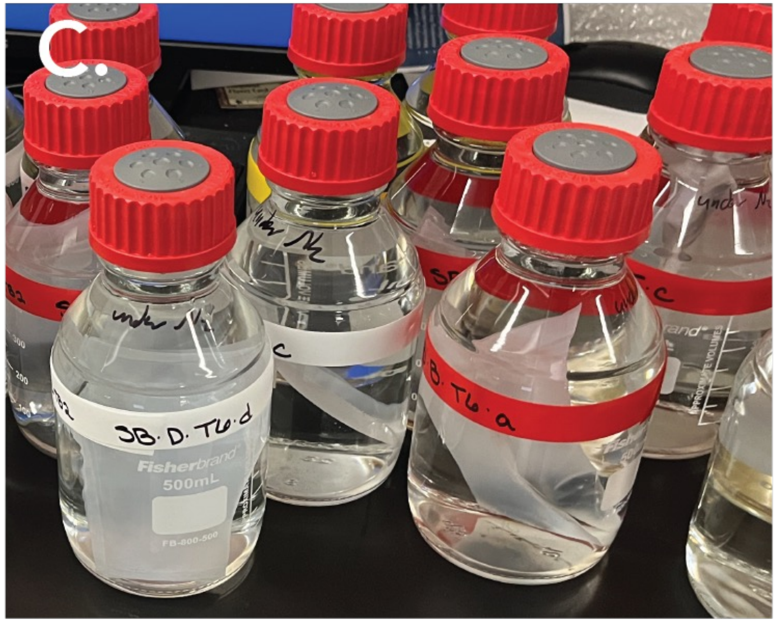
OCRA Data: field deployments and parallel lab experiments



- 5-L Niskin bottles
- ~100 g biomass in 30-μm nylon mesh
- Burn wand timer closes after 3 days
- Recover water and biomass samples after 200 days

DOM leaching rates: Lab experiments





Long-term breakdown experiment

180 days in bottles, 4° C, dark
(no headspace)

----

600 mL sparged water
(90% filtered + 10% living)

+ 2 g biomass in mesh bag

+ 1 mL dilute sediment slurry

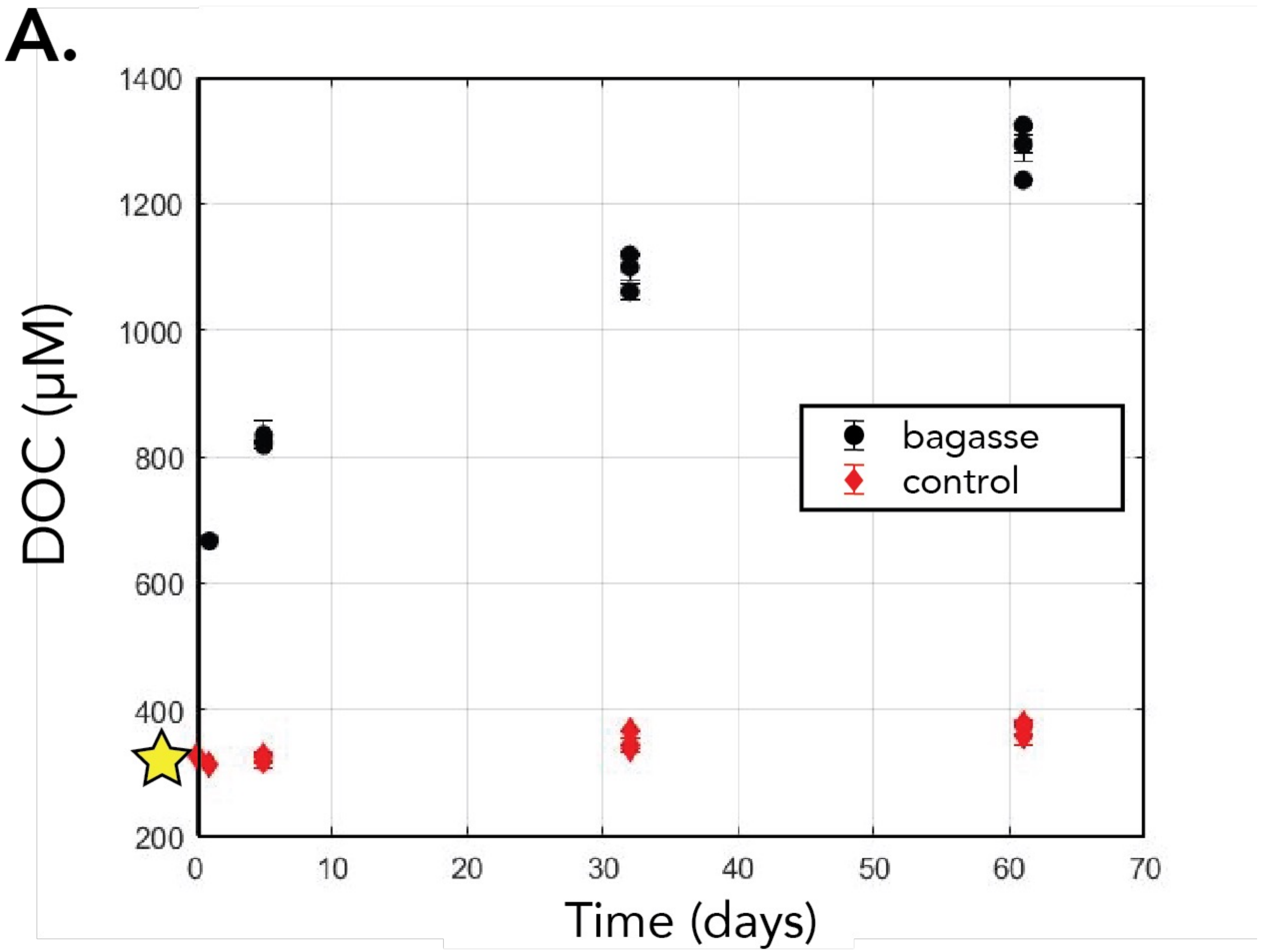
Orca Basin (brine)
vs.
Santa Barbara Basin (seawater)

ongoing!

DOM leaching rates: Lab experiments

The main pathway for C mobilization is *abiotic DOM leaching.*

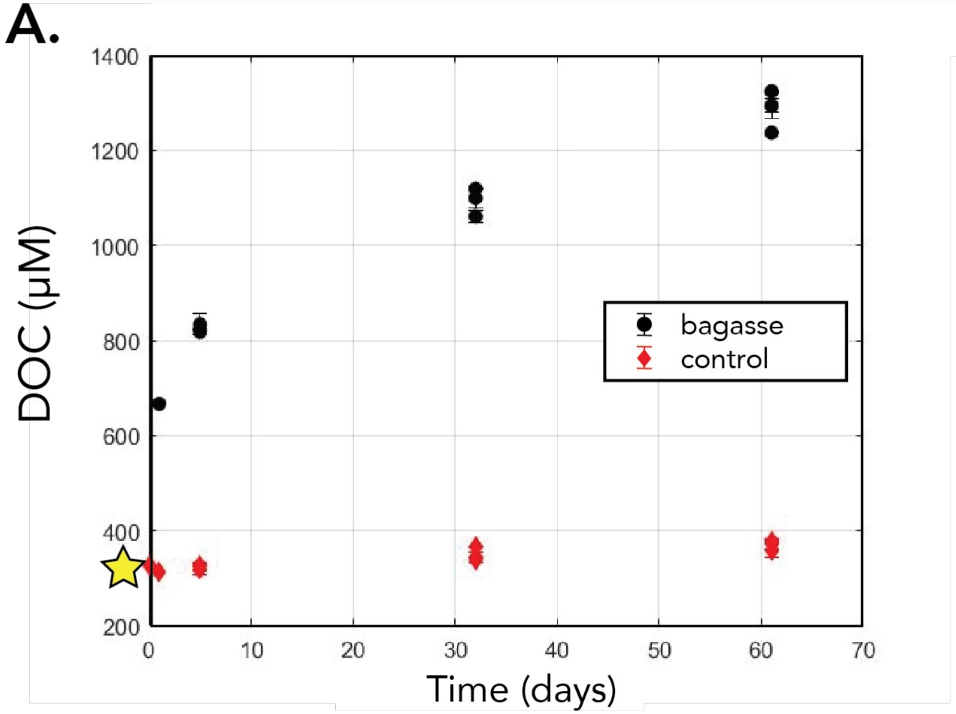
Laboratory experiments, validated against in-situ incubations, can effectively constrain this effect.

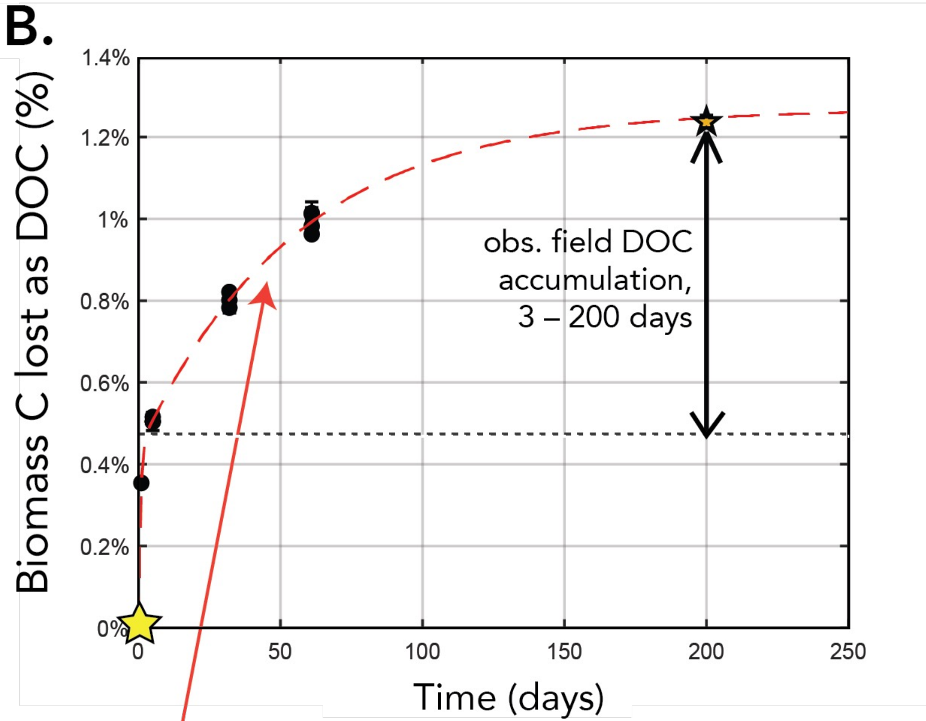


DOM solubilization: compressed bagasse in anoxic brine

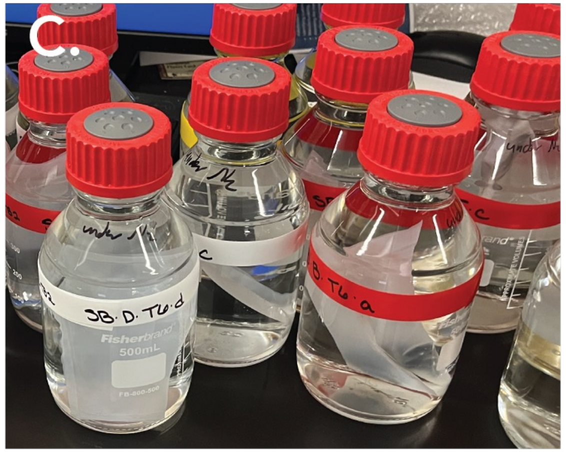
Long-term breakdown experiment, 180 days in bottles

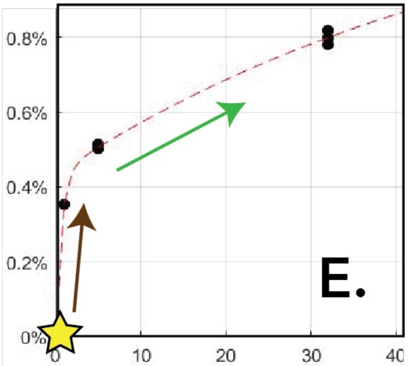
- DOC release by bagasse in anoxic brine reaches 1.27 mol% of initial C after 200 days.
- Highly soluble materials, representing 0.43% of C, leach with a half-life of ~11 hrs.
- Slowly soluble materials, representing 0.83% of C, leach with a half-life of ~38 days.





$$DOC\ loss\ (\%) = \underline{0.434(1 - e^{-t/0.661\ day})} + \underline{0.831(1 - e^{-t/55.3\ day})};\ r^2 = 0.996$$





Evans, Martinez, and Raven, in prep

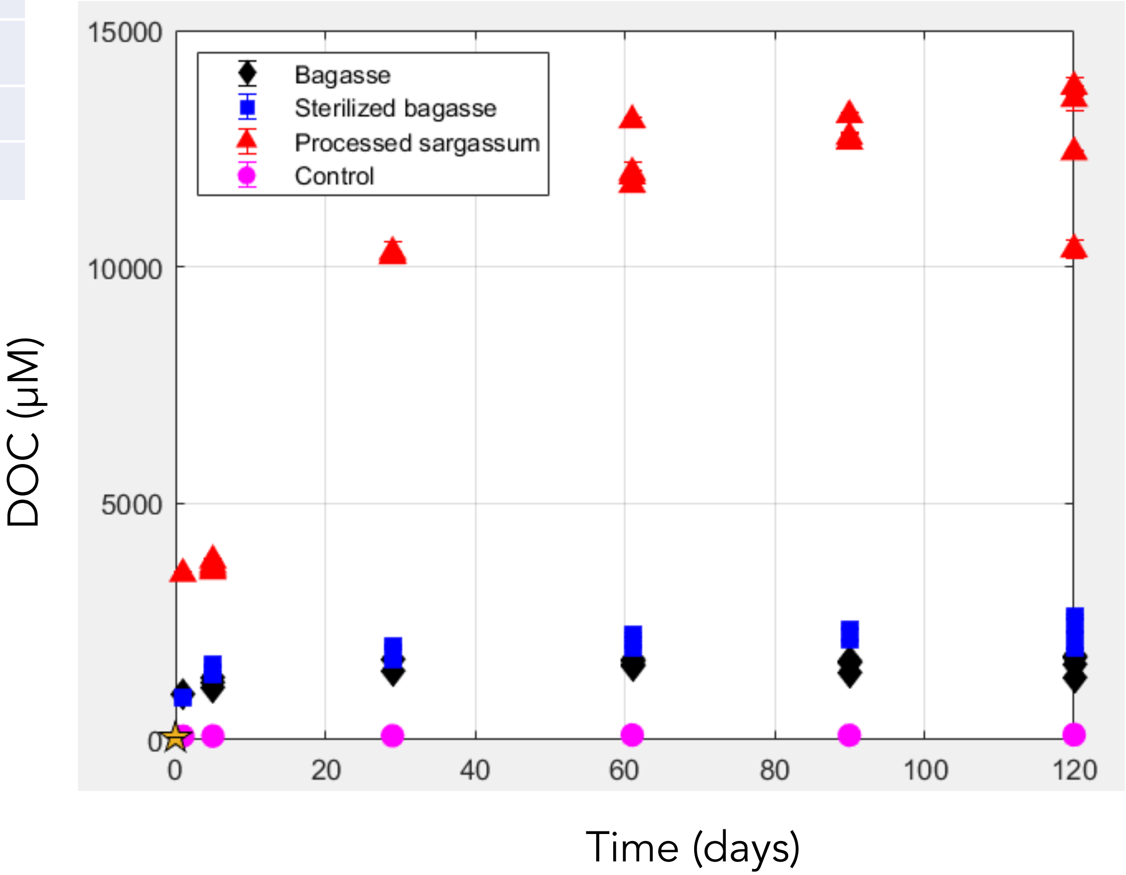
DOM solubilization: compressed bagasse + Sargassum in sparged seawater

Long-term breakdown experiment, 180 days in bottles

Experiment		Highly Soluble		Slowly Soluble		Fit
water	biomass	a1	$\tau_{1/2}$	a2	$\tau_{1/2}$	R^2
		mol% C	day^{-1}	mol% C	day^{-1}	
brine	Bagasse	0.44	0.66	0.83	55.26	1.00
sw	Bagasse	1.00	0.42	0.63	15.26	0.76
sw	γ-Bagasse	1.49	1.24	1.06	73.21	0.87
sw	Sargassum*	2.33	0.05	10.67	18.53	0.96

- Treatment matters: γ-irradiation increases total bagasse solubility.
- DOC release for bagasse is 0.37% higher in sparged seawater than in brine
- DOC release by processed Sargassum represents 13% of total C.

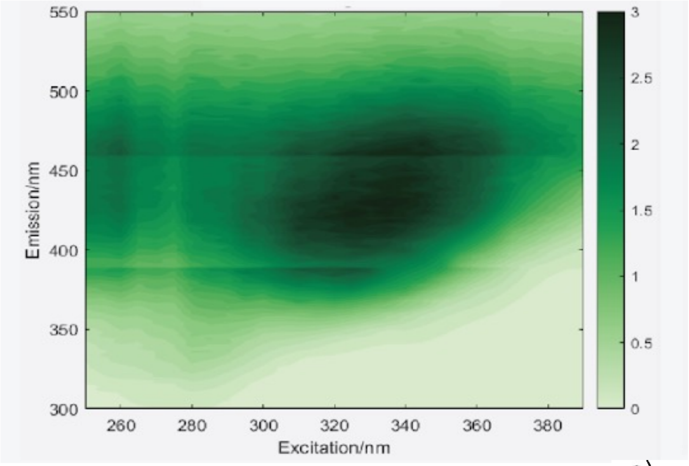
Seawater (Santa Barbara Basin)

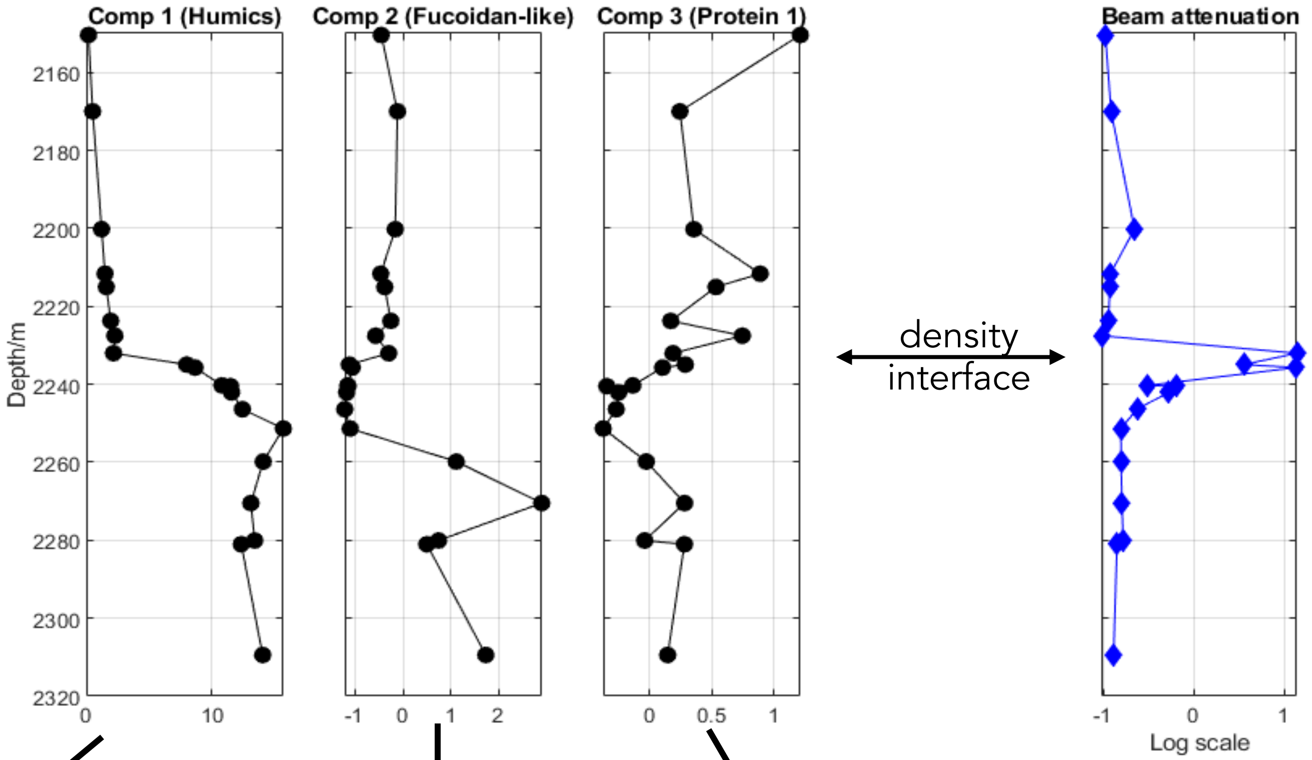


Is bagasse DOM labile in Orca?

Bagasse extracts (as seen in fDOM) chemically resemble background DOM.

Bagasse extract: fluorescence spectroscopy (fDOM)



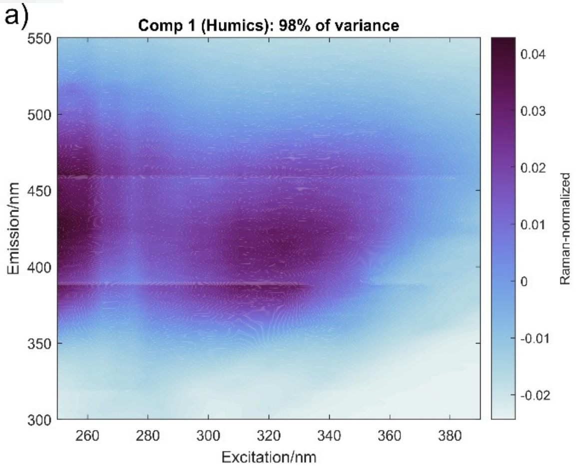


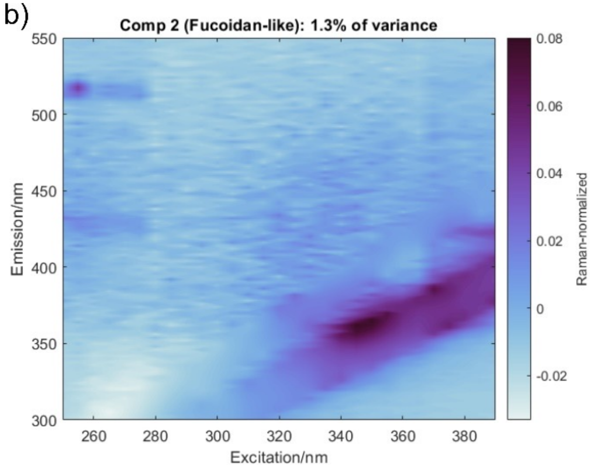
Comp 1 (humics): 98%

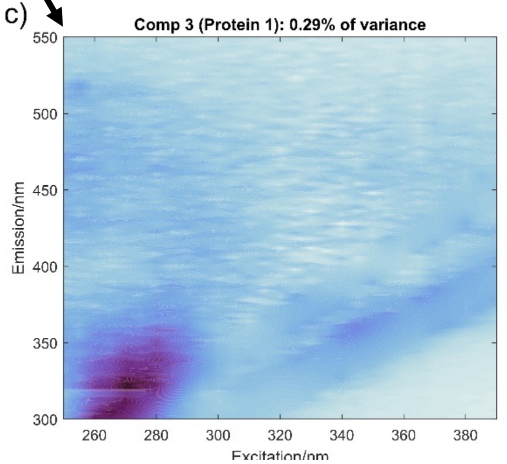
Comp 2 (algae extract): 1.3%

Comp 3 (protein): 0.29%

Principal components of EOF analysis:





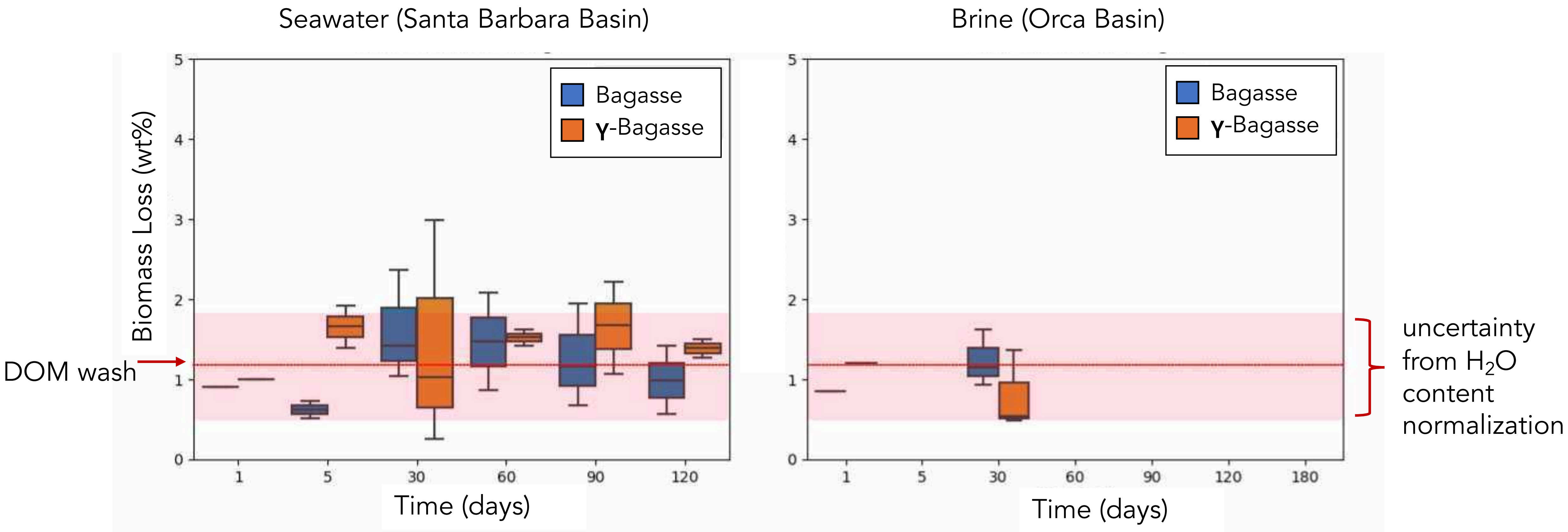


Evans, Martinez, Druschel, Raven, in prep

Microbial breakdown: mass change in biomass bags

Long-term breakdown experiment, 180 days in bottles

- Mass loss from pre-weighed biomass (in 30-μm nylon mesh bags)
- Normalized to controls to account for water lost during salt removal and freeze-drying:
  - No detectable change in biomass solids (+/- 0.6% from water content variability among biomass subsamples (interior / exterior)



Organic matter in Orca brine

Other biomass samples after 200 days

- softwood
- Macrocystis (freeze-dried)

Fossil Holocene seaweed and attached calcareous polychaetes in an anoxic basin, Gulf of Mexico

DURING examination of the planktonic foraminiferal assemblages in a piston-core of black, anoxic sediments (Gyre, 77-G-13, Leg 1, 5-K) of probable early Holocene age from the Orca Basin, northern Gulf of Mexico, we discovered preserved, brown seaweed and calcareous polychaetes from a core depth of 985–1,000 cm. We know of no previous documented case of preserved seaweed in deep-sea sediments, especially with attached organisms, and we describe this material here.

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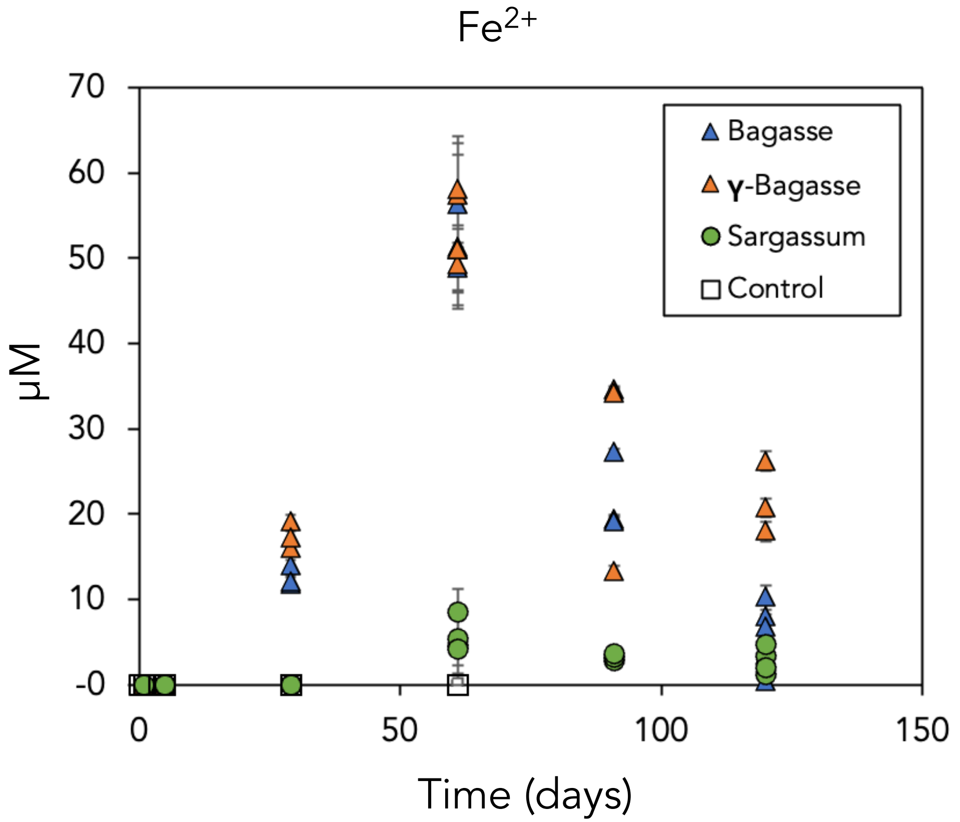
Received 11 July; accepted 18 September 1978.

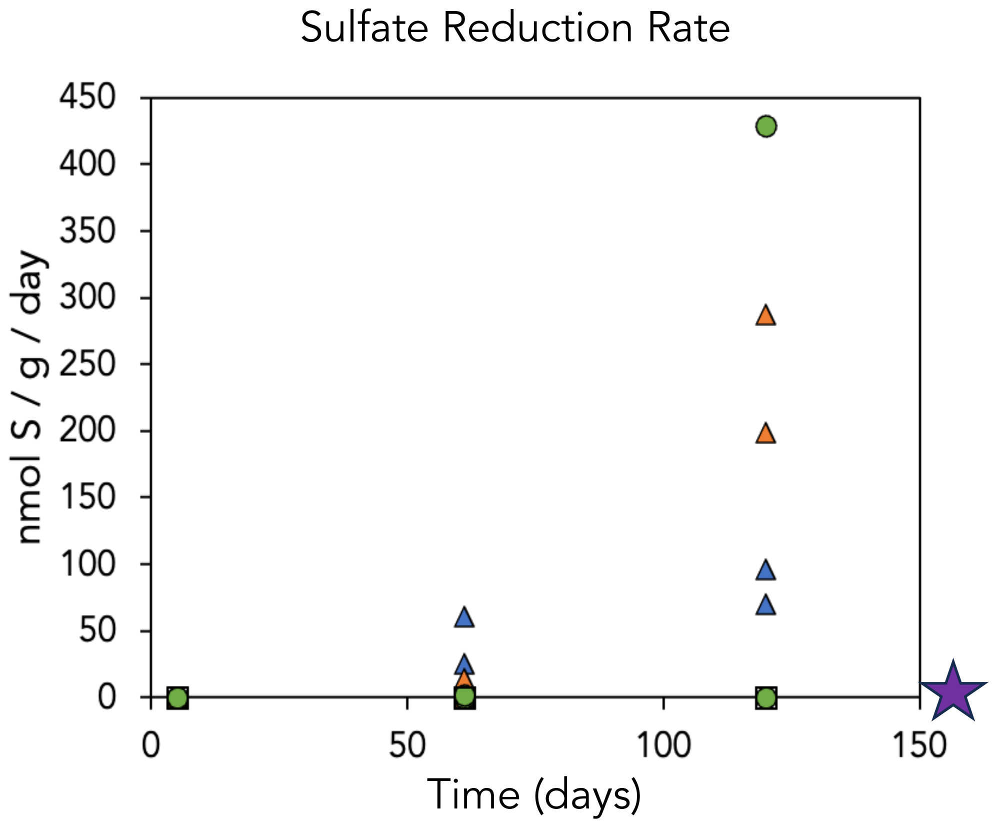
Kennett and Penrose, 1978

Microbial breakdown rates: Fe^{3+} and SO_4^{2-} reduction

Long-term breakdown experiment, 180 days in bottles

Seawater (Santa Barbara Basin)





Brine (Orca Basin) MSR = n.d.

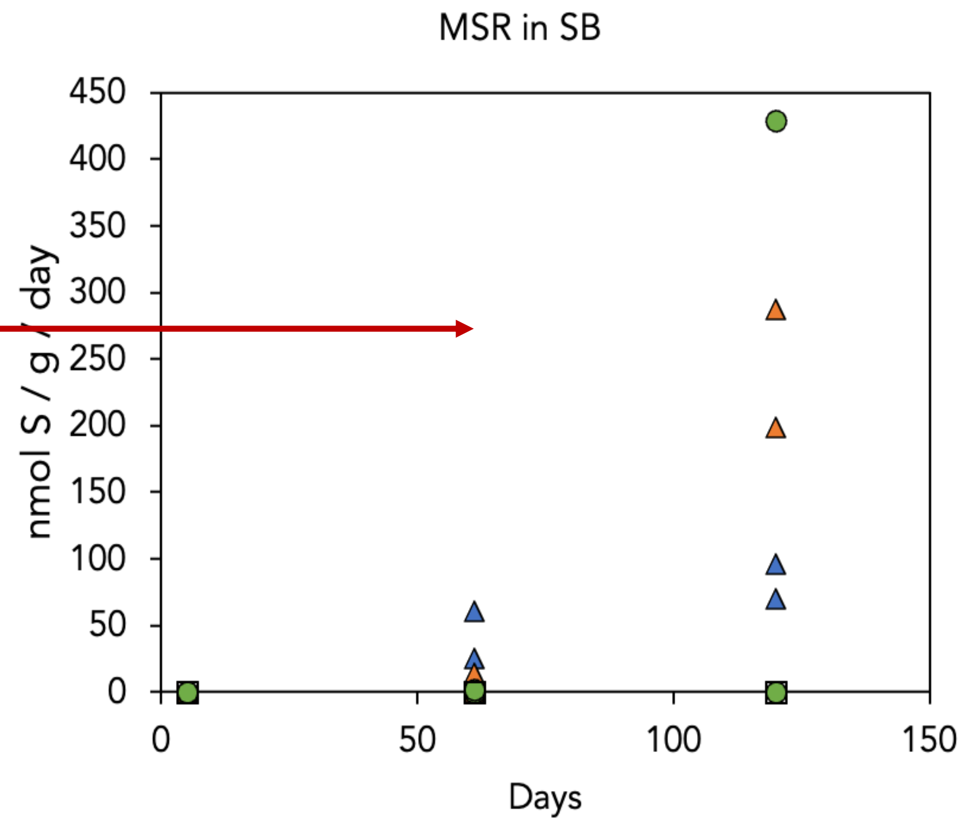
< 2 nmol S / (g biomass) / day; to 60 days

$[H_2S]$ in field incubations < 2 nM after 200 days

Microbial breakdown rates: Fe^{3+} and SO_4^{2-} reduction

Long-term breakdown experiment, 180 days in bottles

Seawater (Santa Barbara Basin)



Peak rates for bagasse in anoxic seawater:

Sulfate Reduction
0.002% / day (of biomass C)
linearly 0.85% / yr, increasing

Iron Reduction
0.0003% / day (of biomass C)
limited after ~60 days

Thermodynamic constraints on metabolisms in Orca Basin

at 5C, 200 bar, activities calculated from GWB

Acetate-based sulfate reduction

$CH_3COO^- + SO_4^{2-} + H^+ == H_2S + 2\ HCO_3^-$ ΔG_R = +128 KJ/mol

Methanethiol-based sulfate reduction

$CH_3SH + SO_4^{2-} + H^+ == S^0 + H_2S + HCO_3^- + H_2O$ ΔG_R = +51 KJ/mol

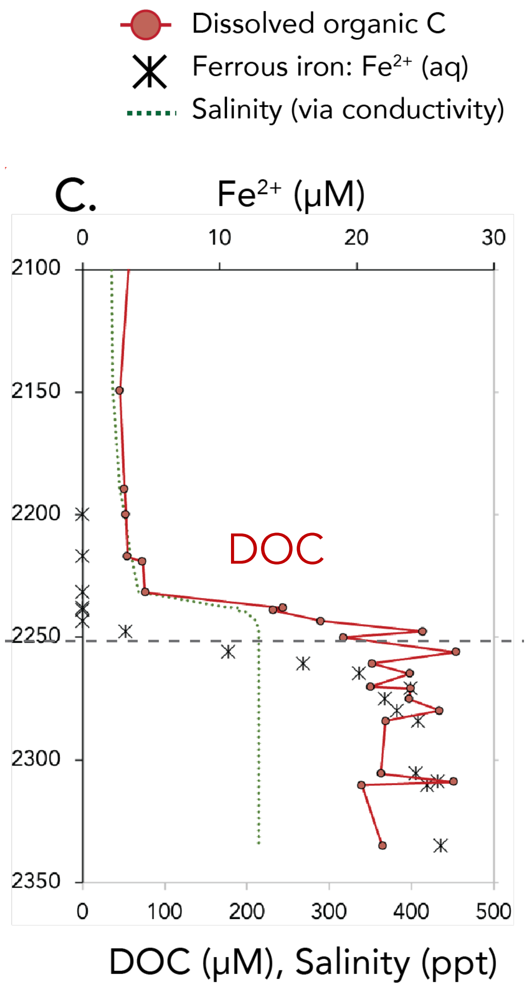
Acetate-based methanogenesis

$CH_3COO^- + H_2O == CH_4 + HCO_3^-$ ΔG_R = –11.6 KJ/mol

Methanethiol-based methanogenesis

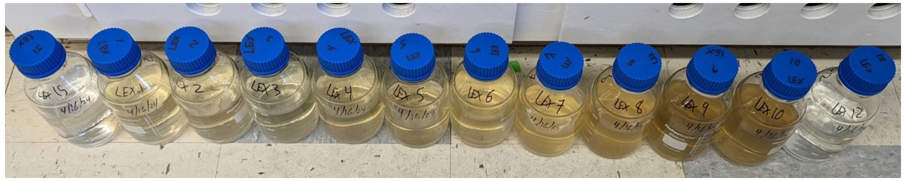
$CH_3SH + H_2 == CH_4 + H_2S$ ΔG_R = –11.4 KJ/mol

Active breakdown pathway : methylotrophic methanogenesis
(radiolabeled incubations; Zhuang et al., 2018)



Conclusions: Short-Term Response (biomass addition to Orca brine)

In Orca brine, the main process affecting biomass C (in bagasse and sargassum) over timescales of hours to months is DOM solubilization.



Compressed bagasse loses ~1.3% of its C as DOC.
Depends on biomass preparation and water properties.

Compressed bagasse experiences slow breakdown through microbial iron and sulfate reduction over 200 days in anoxic seawater, but metabolism is not detectable in brine. <*ongoing*>

Lab data, field experiments, and analog sites can provide valuable data to inform both prognostic models and MRV strategies.

Overall: terrestrial biomass stored in Orca Basin appears stable on 100+ year timescales.

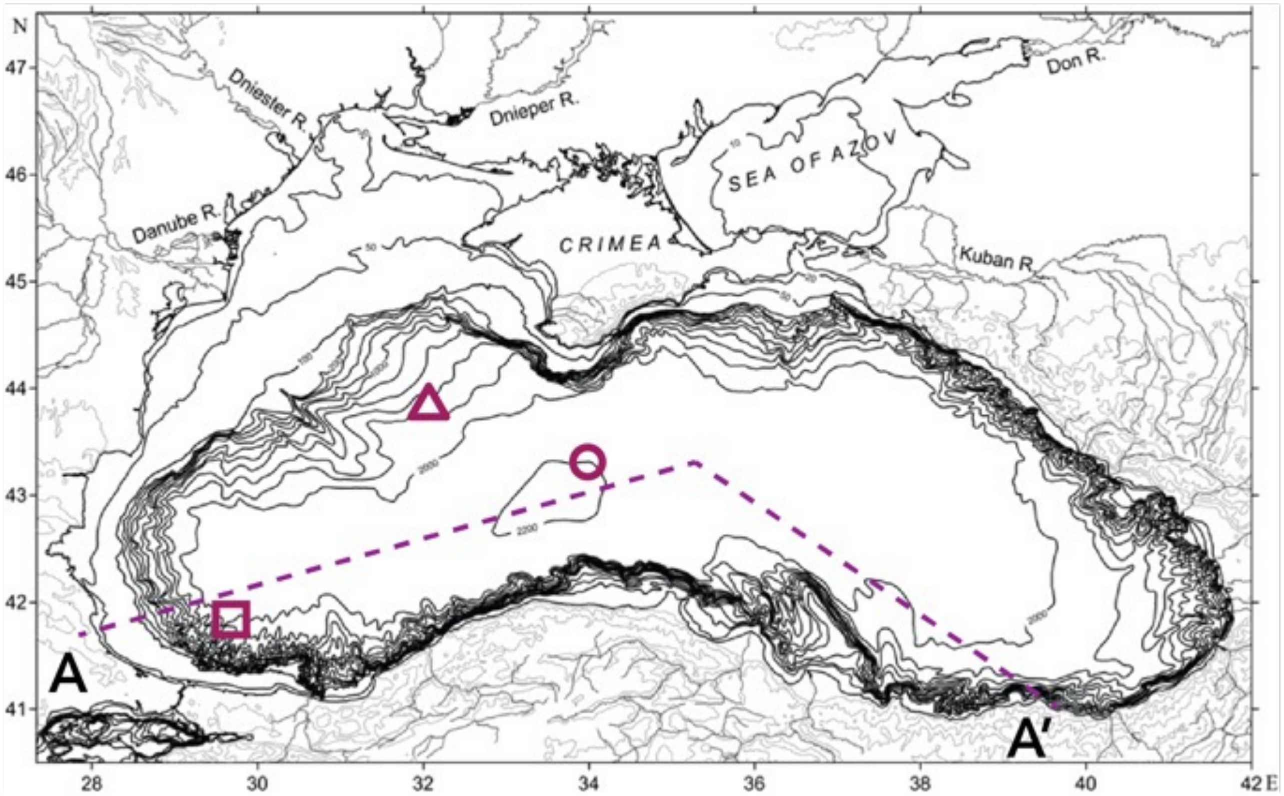
Evans, Martinez, and Raven, in prep

Potential for larger scales?

Black Sea (322,367 km^2) sulfidic water @ 100 – 2200 m depth

Ideal Site Criteria:

- restricted (relatively closed-system)
  - long flow path(s) to surface
- avoids use conflicts
  - animal and sensitive ecosystems
  - human social and economic needs
- efficient organic matter preservation



Toward a process-informed risk assessment framework for biomass mCDR

There is an urgent need to evaluate perturbation impacts on marine ecosystems…

and much more

Perturbation from Intervention	Impact on Marine Ecosystems	Relevance: Biotic mCDR methods – Macro Algae Cultiv.	Micro Algae Fert.	Terrest. Biomass Dump.
Addition of micro- or macro- nutrients (Fe, N, P, Si)	Relieved nutrient stress increases magnitude of global NPP[1]	Med	High	None
	Downstream nutrient robbing shifts global distribution of NPP[1]	Med	High	None
	Shift in balance of nutrients favors different primary producers[1]	Med	High	None
Creation of new biomass	New habitat and food for grazers modifies surface ocean ecosystems	High	Med	None
	Shelf shading shifts vertical distribution and magnitude of local NPP[1]	Med	Med	None
Physical transport of biomass	Sinking of fertilized/deposited biomass smothers benthos	High	Low	High
	Sinking/advected biomass transports passenger organisms and viruses	High	Low	Low
Dissolved organic matter and gasses released from biomass	Highly labile DOM provides food for bacteria and other organisms	High	Low	Low
	Increased DMS production increases cloud formation and cools ocean[4]	Med	Med	None
	Increased N_2O production acts as greehouse gas and heats ocean [4]	Low	Low	Low
Breakdown and respiration of biomass	Deep biomass attracts opportunistic scavengers/invasive species	High	Low	High
	Aerobic respiration consumes O_2 can create anoxic/hypoxic conditions in local/downstream water columm	High	High	High
	Anaerobic respiration produces sulfide, which is toxic until oxidized	Med	Low	High
	Respiration releases nutrients and can affect pH, locally or downstream	High	Med	Med

Roberts et al., in prep

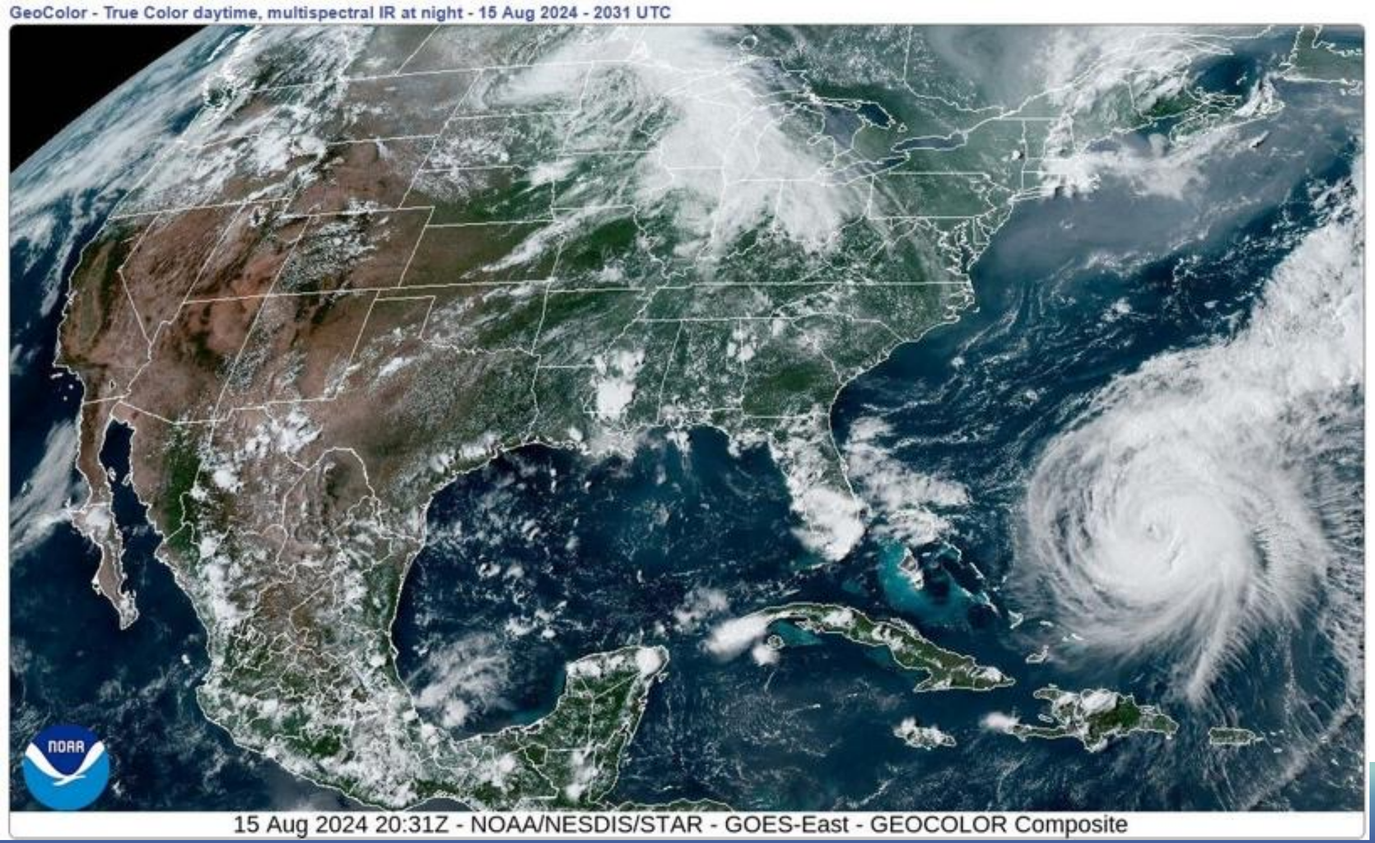
Predicting and monitoring outcomes for biomass mCDR:
hard but not impossible

We need to make big decisions about mCDR on the basis of small experiments.

To do this well, our research strategy must be targeted to improve process-based models that can predict the likely outcomes of different alternative (non)-interventions.

With careful choices about **biomass type** and **sequestration site**, biomass-based mCDR has potential to contribute to net-negative CDR efforts.

These same experiments provide an unprecedented view into Earth's climatic and biogeochemical feedbacks.



Thanks, everyone


OCRA–1


OCRA–4


OCRA–3


OCRA–2

UC **SANTA BARBARA**

Captains Nic Allen and Tad Berkey
Grace Fulton, crew of the R/V *Point Sur* and the R/V *Pelican*

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Carboniferous

https://github.com/UCSB-NOISELab/OCRA

- Bottle incubation method
- Seawater and brine sampling methods
- OCRA 1–4 cruise report