MRV for Seaweed CDR: What is Needed??

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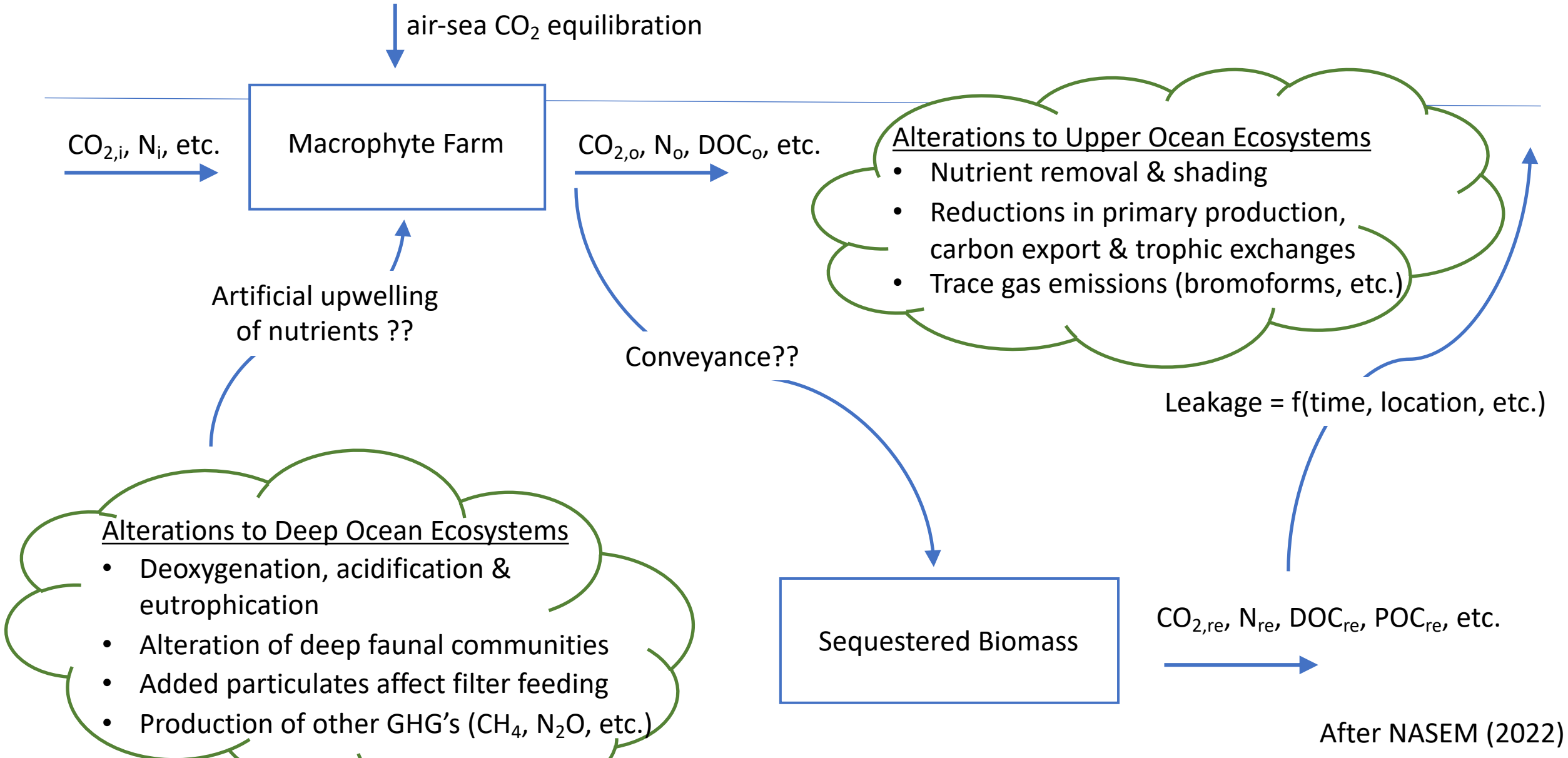
arpa·e OPEN 2021 Award

General Requirements for Ocean CDR

- Must remove atmospheric CO_2 in net
- Must be verifiable in a transparent manner
- Must be durable (CO_2 sequestered must remain isolated from the atmosphere over a known planning horizon)
- Should contribute to the ≥ 20 Gt CO_2 needed to be removed from the atmosphere (≥ 0.1 Gt CO_2/y)
- Quantify intended environmental impacts & place bounds on the unintended
- Address the host of social, legal, regulatory, policy, and economic impacts and concerns associated with the CDR action
- Examine the biophysical & social interactions, synergies, additionalities & tensions among CDR approaches, mitigation, and adaptation

After the NASEM (2022) Ocean CDR Research Agenda Report

Seaweed CDR in a Nutshell



After NASEM (2022)

Seaweed CDR Project

Goal: Assess the efficacy & environmental impacts of seaweed CDR focusing on Giant Kelp & the US west coast building assuming that ARPA-E MARINER program's goals are achievable.

Questions to be answered:

- How does farm design, biomass packaging, conveyance to depth & farm/sequestration site control the efficacy of seaweed CDR?
- What is the displaced primary production & export? Will seaweed CDR work in net & how will it affect ecosystems & C cycling?
- What are the biogeochemical fates of macroalgae C during growth & after sequestration & how do they affect ocean ecosystems?
- Where is seaweed CDR best conducted?

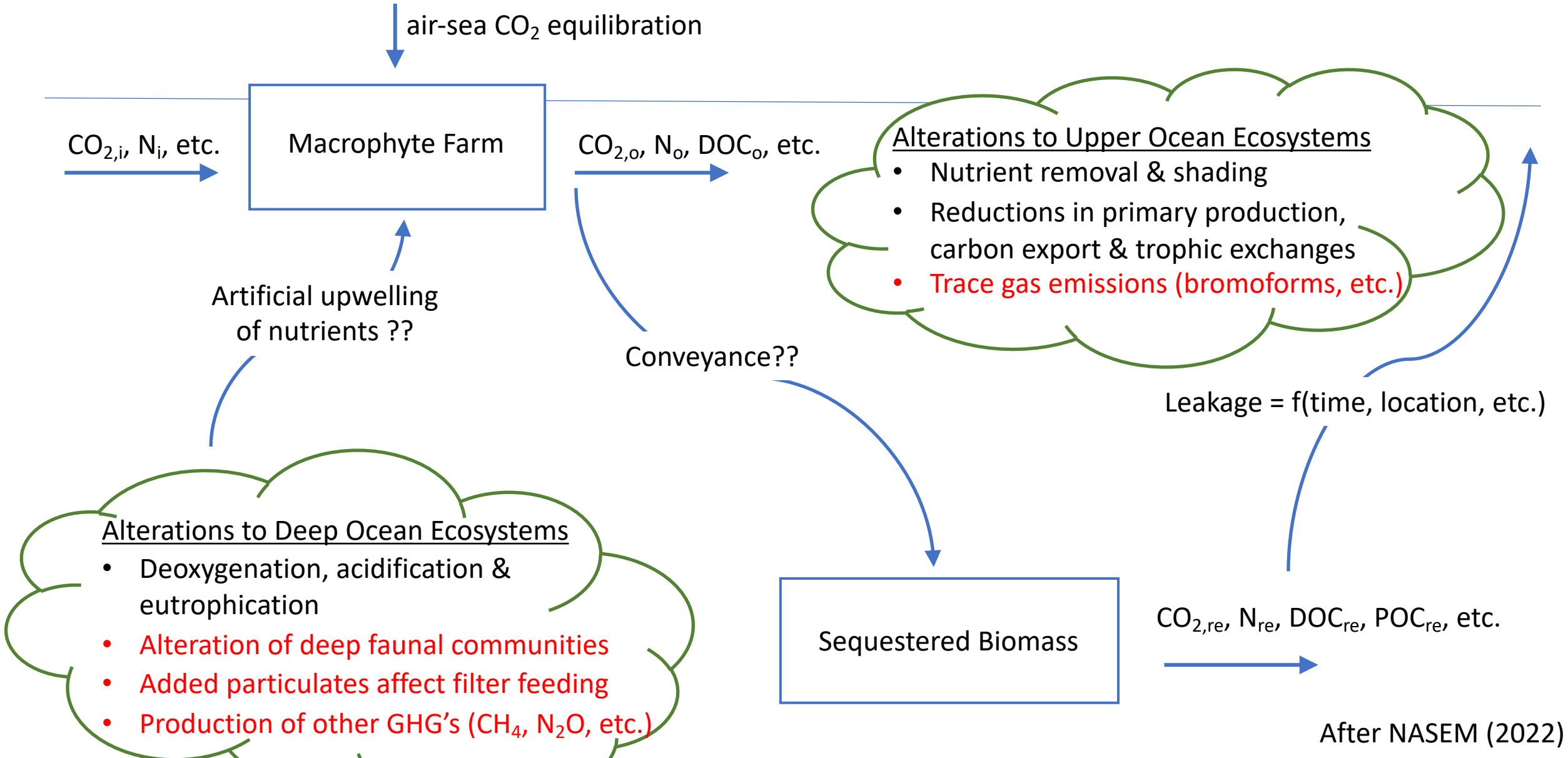
Seaweed CDR Project

Approach: Develop numerical models to assess seaweed CDR efficacy & environmental impacts given a set of farm / sequestration scenarios

Planned Project Steps:

- Develop a set of plausible farm / sequestration scenarios,
- Conduct Giant Kelp biomass & excreted DOM decomposition experiments over a range of packaging approaches & conditions,
- Model the efficacy & impacts of each scenario on regional scales using ROMS & MARINER-developed models for large-scale farm,
- Link to global models providing sequestration time metrics,
- Conduct spatial planning to evaluate appropriate sites, and
- Establish & publish measurement protocols & other T2M activities

Seaweed CDR Project Model



After NASEM (2022)

So, what is needed for Seaweed CDR MRV?

Scale of the Problem:

- Growing enough Giant Kelp to sequester 0.1 Gt CO_2 / year will require at least 70,000 km^2 (~250 km on a side), which suggests a global network of farms

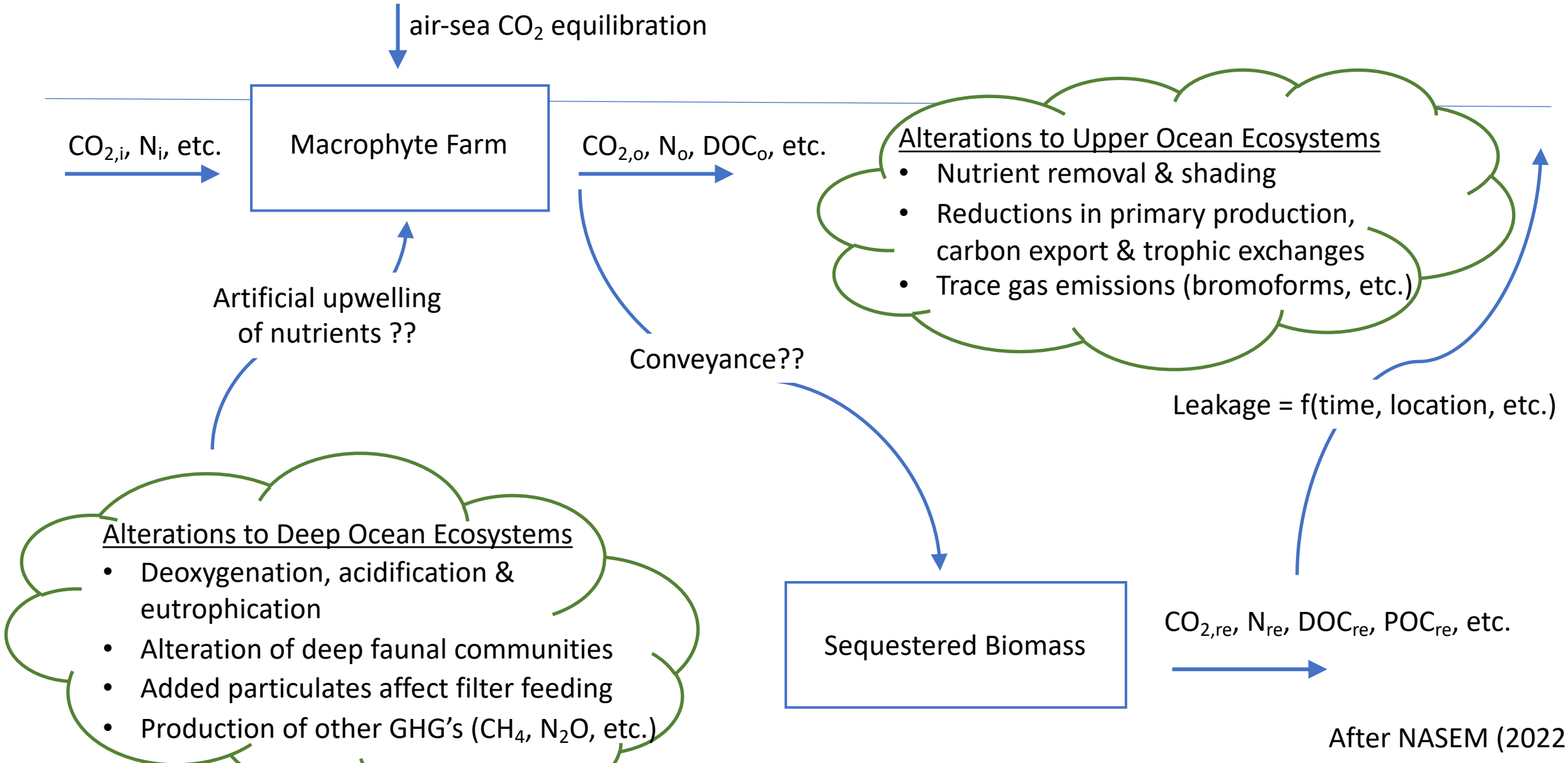
What is needed for Seaweed CDR MRV:

- Regional scale numerical models & observations of key processes
- Validate models with in situ observations over range of conditions

  Need to predict both CDR efficacy & impacts correctly

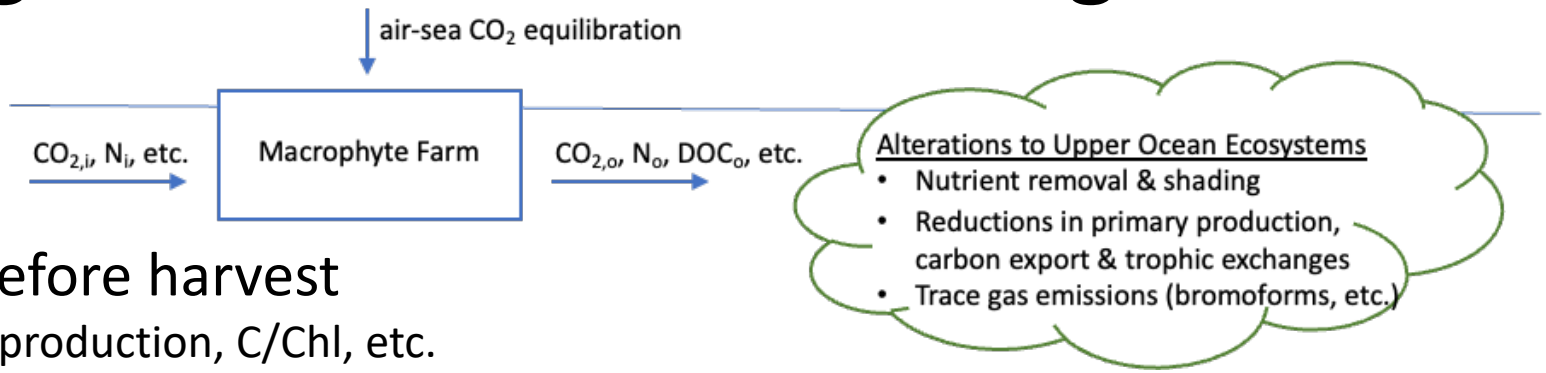
  May not need complete end-to-end pilot studies – farming can be assessed separate from sequestration of biomass on the seafloor
- Low-cost sensor systems for key observables for verification for at-scale CDR
- Extend to other macroalgae species with CDR potential

So, what is needed for Seaweed CDR MRV?



After NASEM (2022)

MRV for Large-scale Seaweed Farming



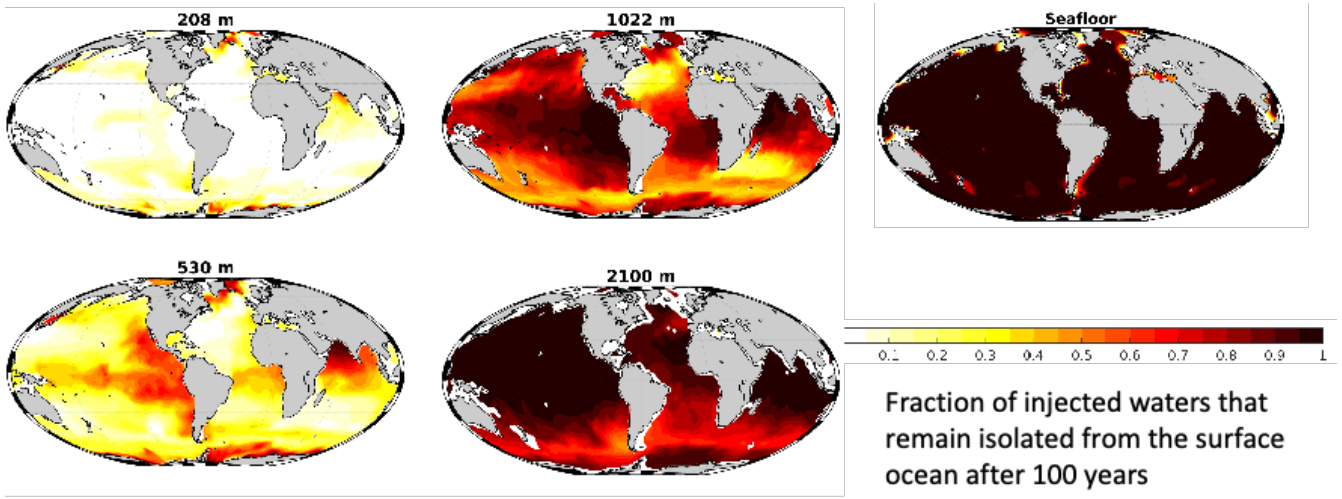
Knowledge Required:

- Evaluate the farmed seaweed before harvest
  Seaweed biomass, C/N content, primary production, C/Chl, etc.
- Assess environmental conditions "inside & outside" of farm environment
  Nutrients, light, phytoplankton (abundance & community structure), CO_2, DOC, DOC quality, mixing & residence times, higher trophic levels, etc.
- Measure carbon export & its vertical attenuation "inside & outside" of the farm
  Sinking carbon flux as function of depth – More on this in Ken Buesseler's talk
- Evaluate production and air-sea exchanges of trace gasses

Potential Measurement Systems:

- Instrumented autonomous vehicles surveying from "inside to outside" of the farm
  Above water sensing (drones or satellites) may be useful for farms growing canopy forming species
- Most sensors needed are of pretty high TRL with some exceptions (DOC, DOC quality, sinking C export fluxes, water mass residence times within farms, multi-freq acoustic sensors for seaweed biomass)

MRV for Conveying Seaweed Biomass to Depth



Fraction of injected waters that remain isolated from the surface ocean after 100 years

Siegel, DeVries, Doney & Bell (2021)

Issue:

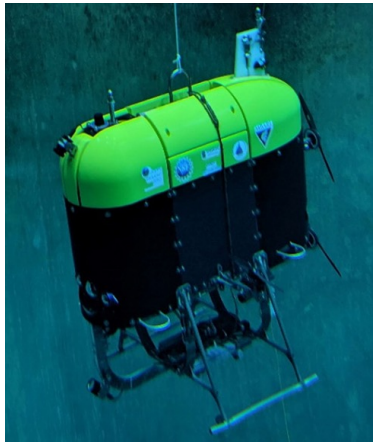
- Durability is strong function of depth
- A reasonable goal is >2000 m or on seafloor
- Need vertical profile of biomass degradation

Knowledge Required:

- Sinking rate of farmed biomass as function of packaging
  Whole plants or farmed lines, bales of various sizes, masticated biomass, etc.
- Degradation rates & products (DIC, DOC, POC, etc.) of biomass as function of packaging
  Over a range of oceanographic conditions (T, O_2, etc.) and depths

Potential Measurement Systems:

- Models can be created from field / laboratory experiments
- Validation of models may require autonomous vehicles capable of following sinking biomass & sampling the environment surrounding it
- WHOI's MESOBOT is designed to follow & study large organisms in the deep sea



Yoerger et al. 2021

MRV for Fates of Sequestered Biomass

Sequestered Biomass → $CO_{2,re}$, N_{re}, DOC_{re}, etc.

Alterations to Deep Ocean Ecosystems
- Deoxygenation, acidification & eutrophication
- Alteration of deep faunal communities
- Added particulates affect filter feeding
- Production of other GHG's (CH_4, N_2O, etc.)

Knowledge Required:

- Fates of seaweed biomass within the water column & on seafloor
  Degradation rates & products (DIC, DOC, POC, nutrients, O_2 consumption, etc.)
- Biogeochemical impacts (ΔpH, ΔO_2, etc.) & their spatial extent above sequestration sites
  Spatial mapping of the impacts around depositional sites as a function of the amount & packaging of biomass
- Ecological impacts on benthic sediment biogeochemistry & faunal communities
  Spatial extent, magnitude and impacts as a function of the amount & packaging of biomass, characterize differences in sediment biogeochemistry & faunal communities due to the deposition of biomass on the seafloor

Potential Measurement Systems:

- Biogeochemical & imaging sensors on autonomous vehicles surveying depositional sites
  Sensors to measure gradients in water column impacts (ΔpH, ΔO_2, ΔDOC, etc.) & to provide data to constrain models of biomass decomposition, imagers to assess faunal distributions in water column & on seafloor
- Benthic observatories
  Spatial mapping of the impacts around depositional sites as a function of the amount & packaging of biomass

Thoughts about Sensors for Seaweed CDR MRV

- Sensors & autonomous platforms already exist for many of the tasks

  Off-the-shelf sensors for Chl, O_2, NO_3, pCO_2, light levels, absorption & scattering, aggregate & metazoan imaging, export flux from imagery, benthic imagers, acoustic backscatter, as well as autonomous vehicles, docking stations, underwater navigation, etc. all exist today. That said, improvements are needed!!

  Algorithms have been developed that relate these electronic measurements to carbon stocks & fluxes

- High-throughput sensors for DOC & DOC quality

  Outside of terrestrially dominated ocean environments, colored DOM does not relate well to DOC

  Some hope with UV-C wavelengths (≤ 280 nm) for both DOC & quality indices (polyphenols)

- High-throughput sensors for eDNA

  eDNA can target specific taxa or provide broad biodiversity info – need assessments of eDNA fates

  Environmental Sample Processer is great – but relatively low sample throughput – eDNA on a chip??

- Seafloor observatories for assessing impacts of “at scale” biomass inputs

  Spatial assessment of sediment profiles, faunal mapping, AUV surveying, etc.

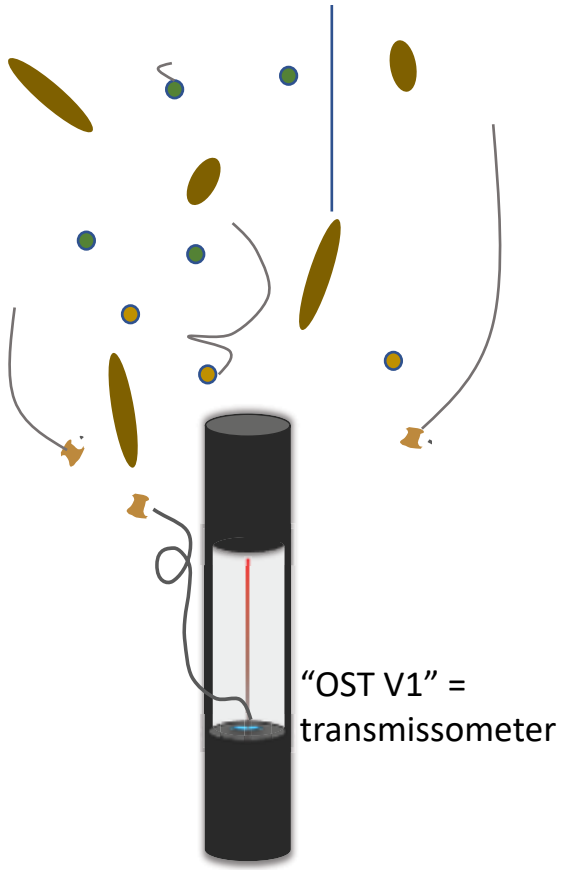
- Challenge will be creating observational systems to provide actionable MRV info –points to the importance of creating validated system models & deploying OSSE for system design

Thank you for your attention!!

Extra slides…

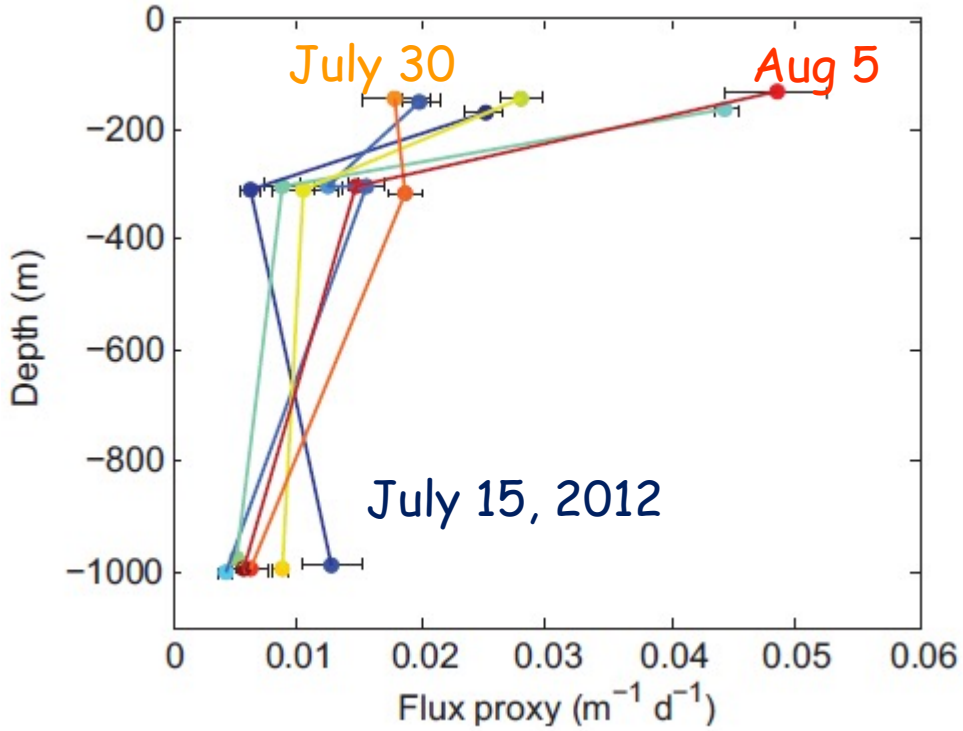
Optical Sediment Trap (OST)

Physical interception and optical detection of sinking particles
Direct flux measurement = no need to assume particle sinking speed
Carbon content must be inferred from light attenuation or images



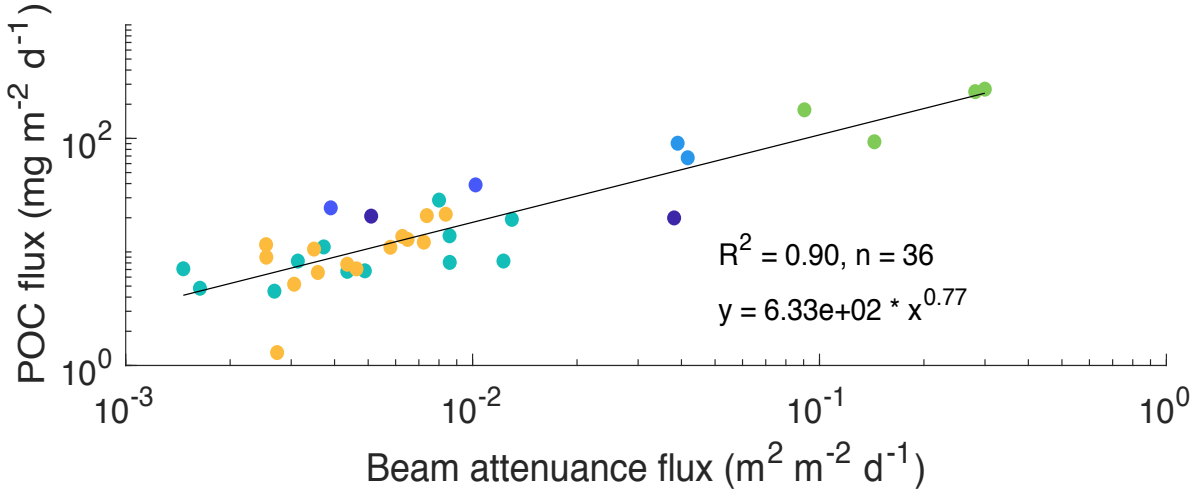
Estapa et al., Bishop et al.

OST at BATS



OST signal of <u>sinking particles</u> over 18-24 hr at BATS- *Estapa et al. 2013*

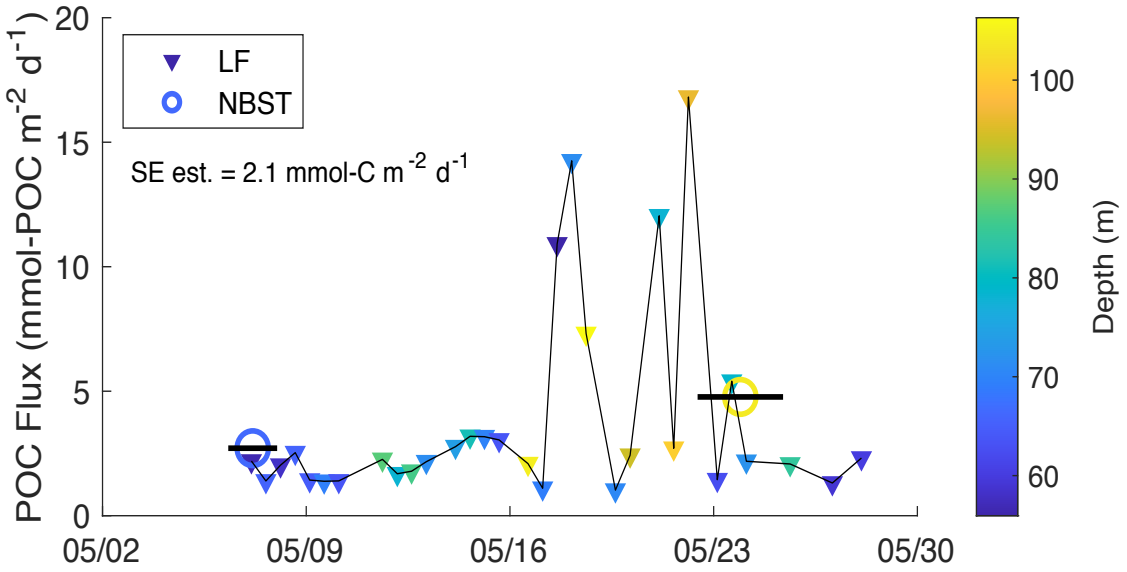
Beam attenuance flux and POC flux are strongly related



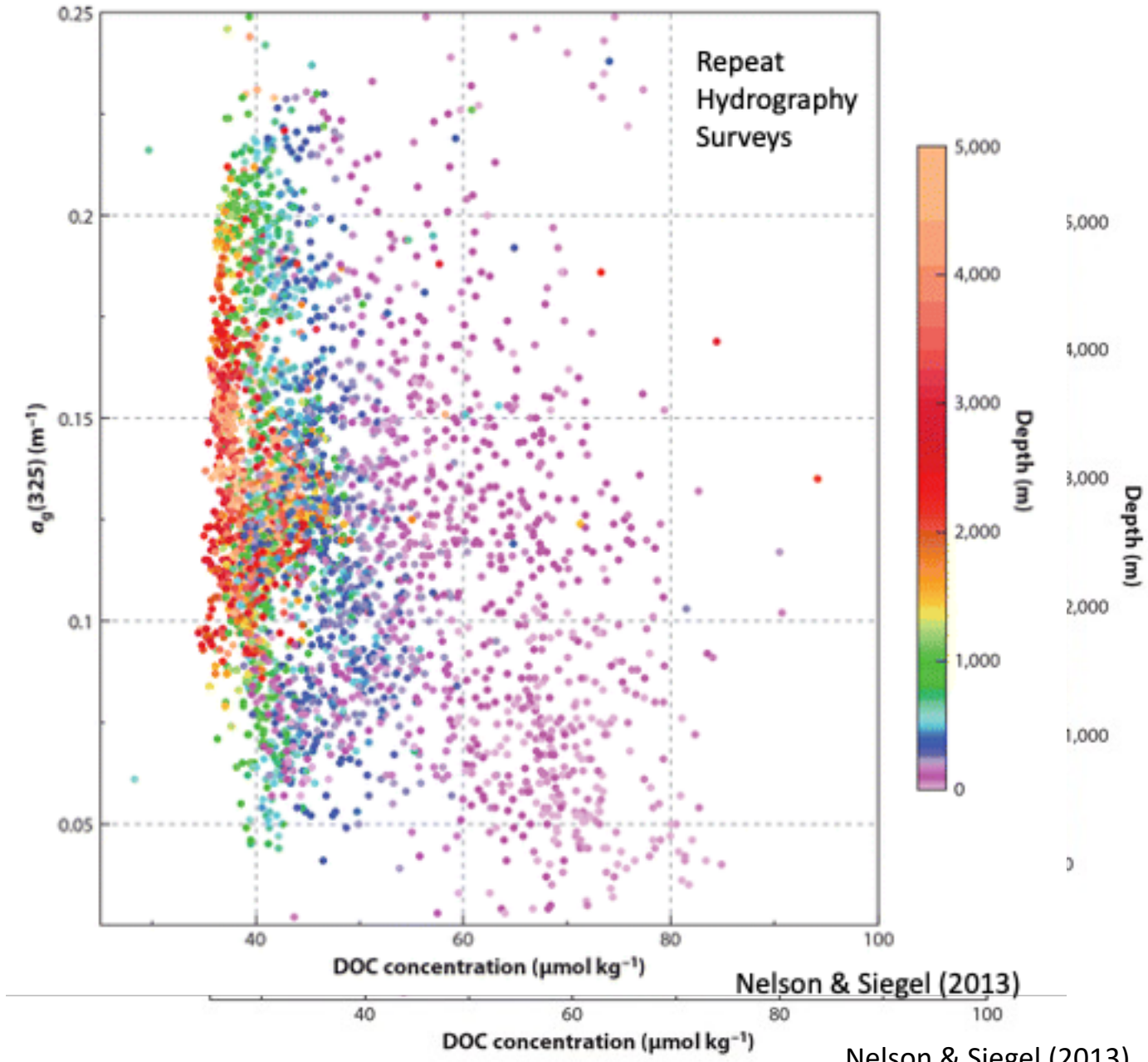
- Subtropical N Pacific
- Subpolar E Atlantic - PAPSO - DY077
- New England coastal
- Subpolar N Pacific - OSP
- Subpolar E Atlantic - PAPSO - EXPORTS
- Subtropical N Atlantic - BATS

Data compilation from published and unpublished sources: Estapa (UMaine), Durkin (MBARI), Omand (URI), Buesseler (WHOI), Baker (NOC).

Onset of high flux from bloom starts on May 17th



Data example from EXPORTS (Estapa (UMaine), D'Asaro (UW/APL), Omand (URI), preliminary/unpublished)



Nelson & Siegel (2013)