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Mitigating nitrogen beyond the source with reactive barriers and bioextraction

Nils Volkenborn, Michael Doall, Chris Gobler

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Treatment of Legacy Groundwater Nitrogen with Permeable Reactive Barriers to Mitigate Coastal Ocean Eutrophication

Stony Brook University
NYS Center for Clean Water Technology

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Jing-An Lin (PhD student)
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Chris Gobler (CCWT Director)
Hilary Brooks (CCWT Administration)

Ron Paulsen (CCE)
Molly Graffam (CCE)
Matt Sclafani (CCE)

Cornell University Cooperative Extension

Funding and Support

NEW YORK STATE OF OPPORTUNITY

Department of Environmental Conservation

Hampton Hills Association
Community Preservation Fund
Town of Southampton
Town of Brookhaven

Acknowledgements

Stony Brook University
NYS Center for Clean Water Technology

Chris Gobler
Stuart Waugh
Frank Russo
Hilary Brooks

Jing-An Lin
Ian Dwyer
Caitlin Asato
Jackie Collier
Xinwei Mao
Qingzhi Zhu

Cornell University Cooperative Extension

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UNIVERSITY OF GEORGIA

Christof Meile

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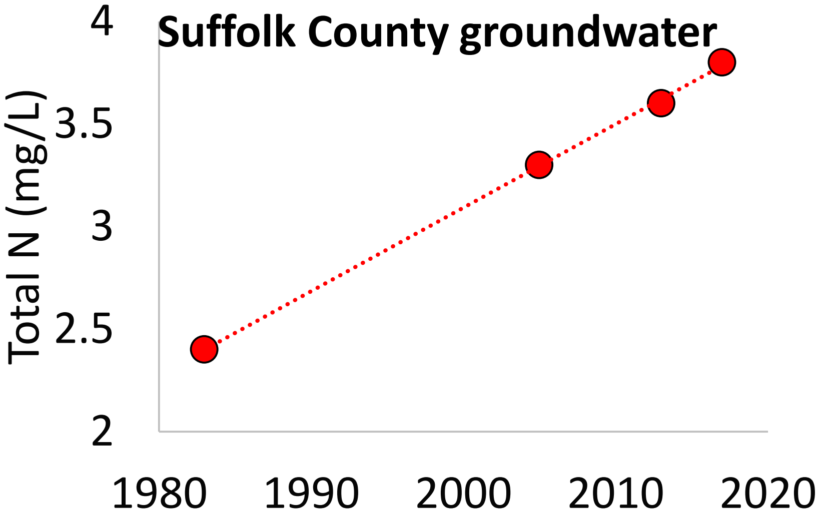
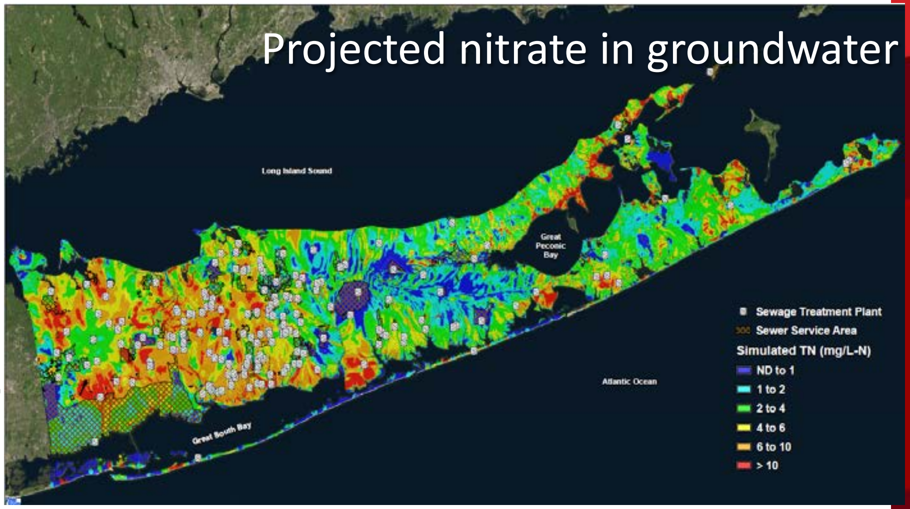
The problem: “Legacy Nitrogen”

- Over the past decades we have loaded Long Island’s aquifers with **nitrogen.**





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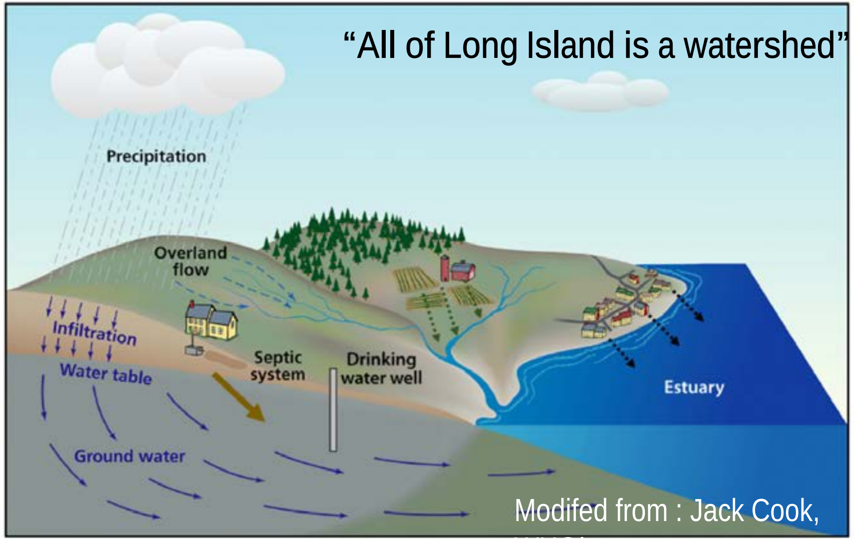
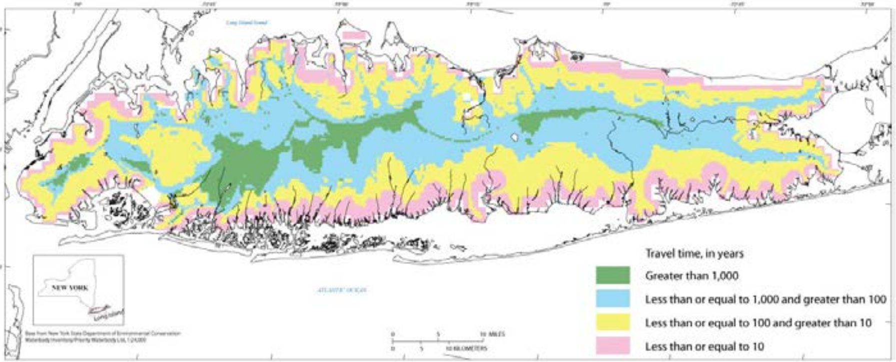
The problem: “Legacy Nitrogen”

- Over the past decades we have loaded Long Island’s aquifers with Nitrogen.
- Eventually this groundwater will enter our coastal bays mainly through submarine groundwater discharge.
- Even if we would stop releasing N to Long-Island aquifers today, this “legacy nitrogen” will continue to seep into our coastal bays *for decades*.



Groundwater Travel Times



Misut and Monti 2016

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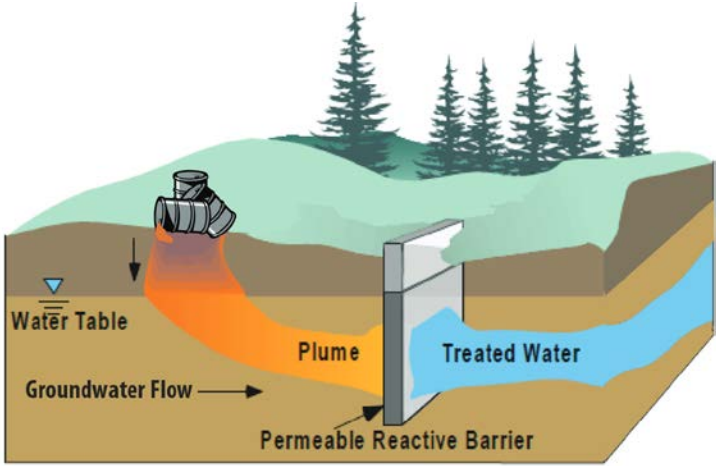
Permeable Reactive Barriers (PRBs) can be part of the cure

- PRBs are below-ground walls with “reactive media” that **intercept groundwater flow** along the natural hydraulic gradient.
- Due to their high hydraulic conductivity, they **attract water from depth.**
- Woodchip-based PRBs can efficiently remove nitrate from groundwater by providing a carbon source for denitrifying soil microbes (analogue to NRBs) (Robertson et al., 2008; Graffam et al. 2020).



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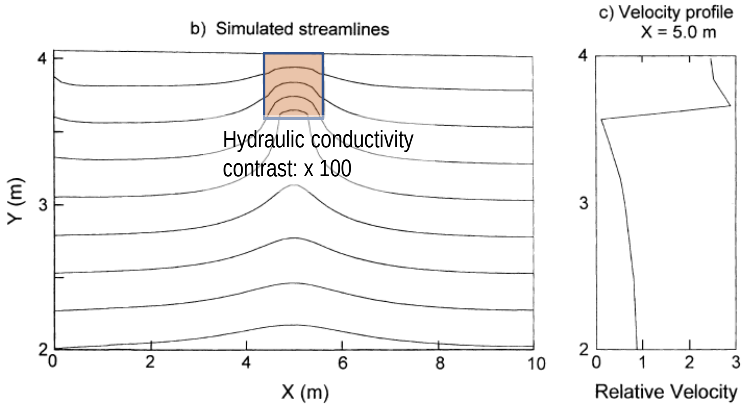

modified from Robertson et al. 2005

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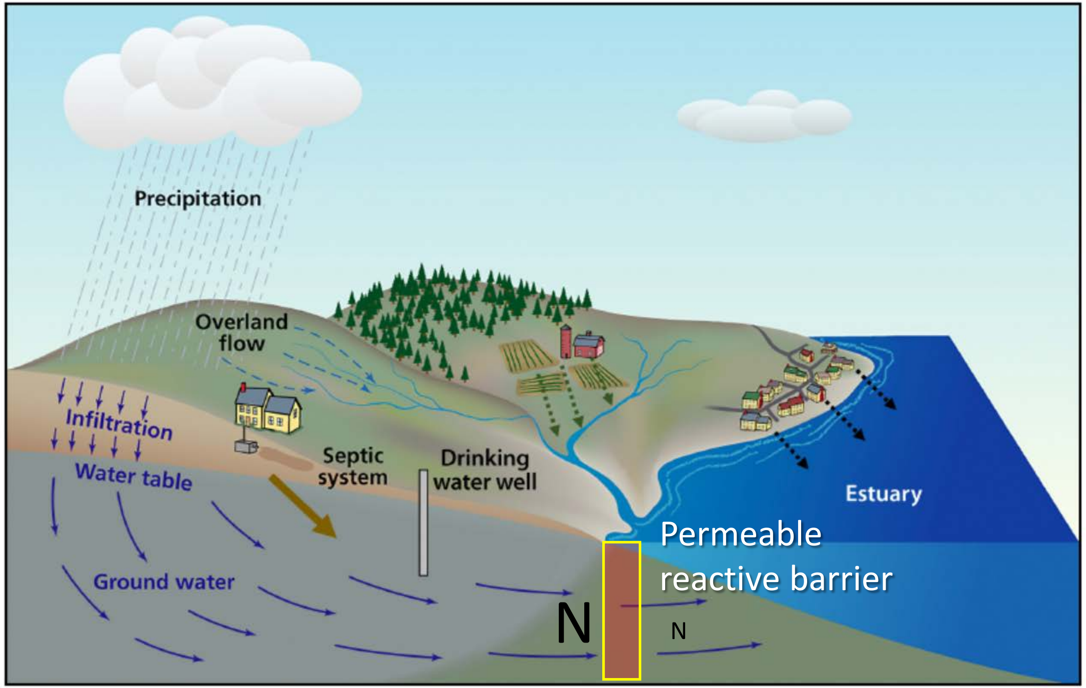
PRB installations close to the shoreline has advantages

- N-loading to impaired surface water bodies is reduced soon after installation.
- Large volumes of groundwater can be treated at relatively shallow depths due to the **vertical convergence** of flow paths above heavy saltwater wedges.
- Other construction activities at the shoreline (e.g., **bulkhead replacement**) can be a cost-saving opportunity to integrate PRBs.

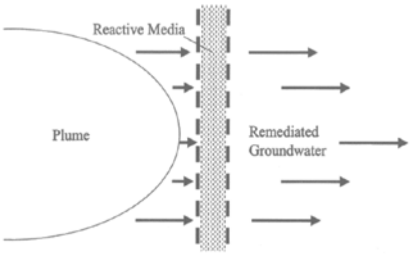


modified from Jack Cook, WHOI

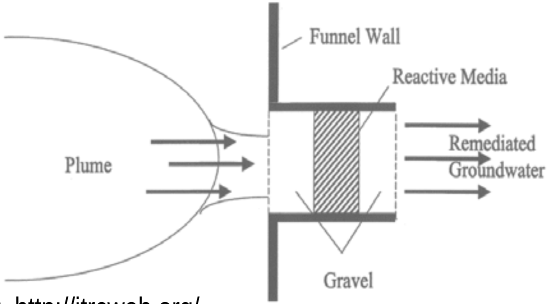
NYS CCWT: Provide science-based recommendations on placement and site-specific PRB design to optimize N-removal performance, while minimizing release of undesired secondary products and minimizing costs.

- Where is a PRB useful and effective?
- Design: trench, funnel-and-gate, woodchip column, or injection well arrays, composition of the reactive media? How thick, wide and deep?
- Cost-benefit ($ per lbs N removed)

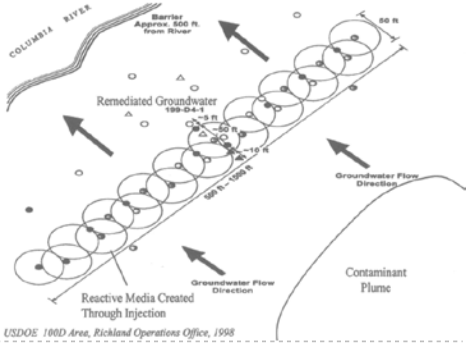
Trench-type PRBs



Funnel-and-Gate PRBs



Column Arrays and Injection Wells



Interstate Technology and Regulatory Council 1999, http://itrcweb.org/

Scientific areas addressed by CCWT

- Preinstallation site characterization
- Nitrate-removal rates considering site-specific conditions (groundwater velocities, NOx concentrations)
- Matrix composition (carbon source, hydraulic conductivity and porosity of reactive media)
- Formation and fate of undesired secondary products (focus on greenhouse gasses and metals)

CCWT activities

- Laboratory flow-through column studies
- Monitoring in-ground systems (some in collaboration with CCE)
- Reaction-Transport Modelling (in collaboration with Christof Meile, UGA Athens)

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Long-term column experiment 2020-2021

upward flow

- Woodchip-pea gravel mixtures aged in a PRB systems for 5-years:
- Oak vs pine vs oak-pine vs maple-cherry (n=3)

Experimental manipulation

- hydraulic retention times / velocities
- Nitrate concentrations
- Temperature

Monitoring

- N-removal
- Greenhouse gas formation
- Oxygen penetration into woodchip media

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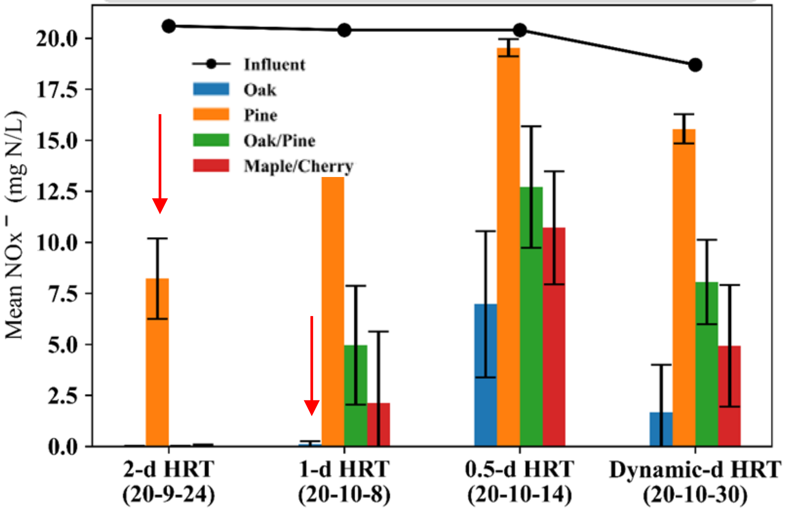
Nitrate Removal

- Sustained N-removal by aged woodchips
- N-removal differs between woodchip media
- Effluent nitrate scales with HRT



~2 ft d^{-1} ~4 ft d^{-1} ~8 ft d^{-1} ~4 ft d^{-1}

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Nitrate Removal

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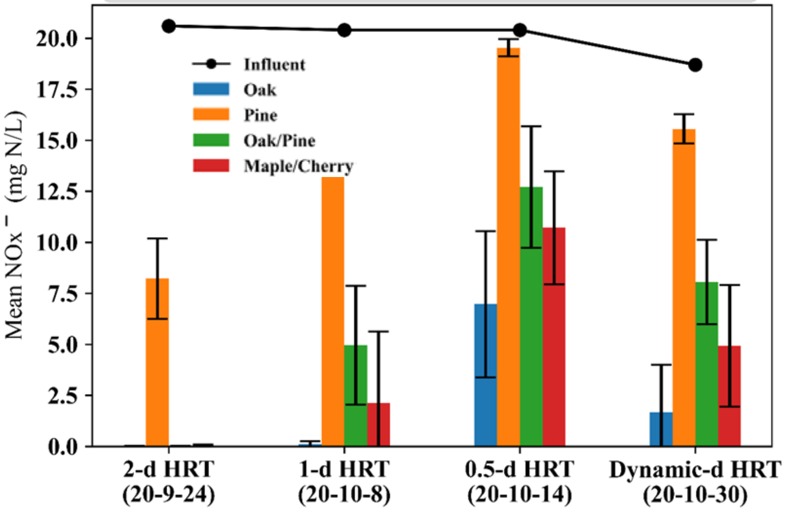
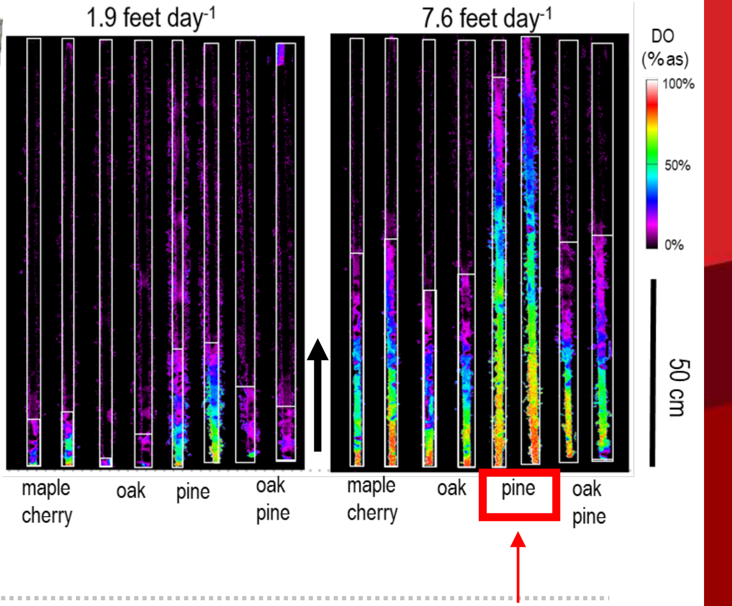


~2 ft d^{-1} | ~4 ft d^{-1} | ~8 ft d^{-1} | ~4 ft d^{-1}

Oxygen Penetration assessed by *Planar Optode Imaging* used to quantify the "loss" of anoxic media that prevents to denitrification at high velocities.



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Pollution swapping!

Nitrate Removal

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- N-removal differs between woodchip media
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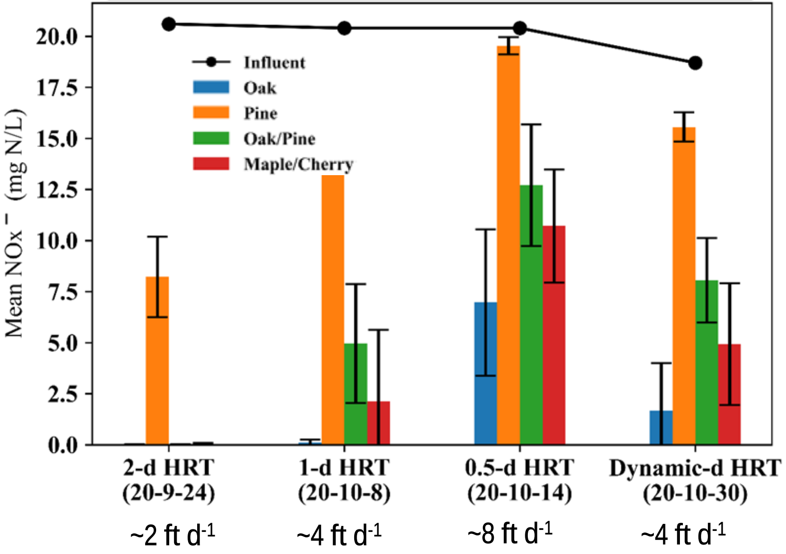
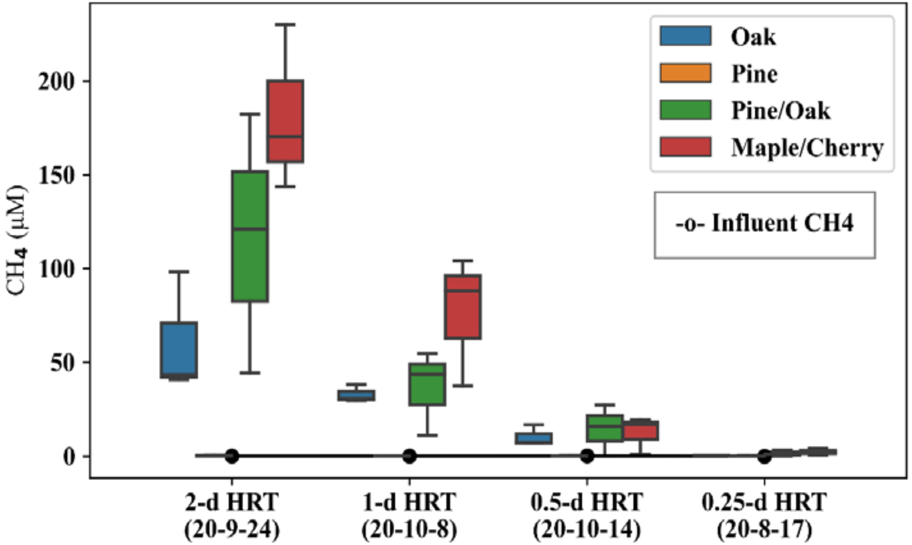


Methane formation when nitrate is depleted

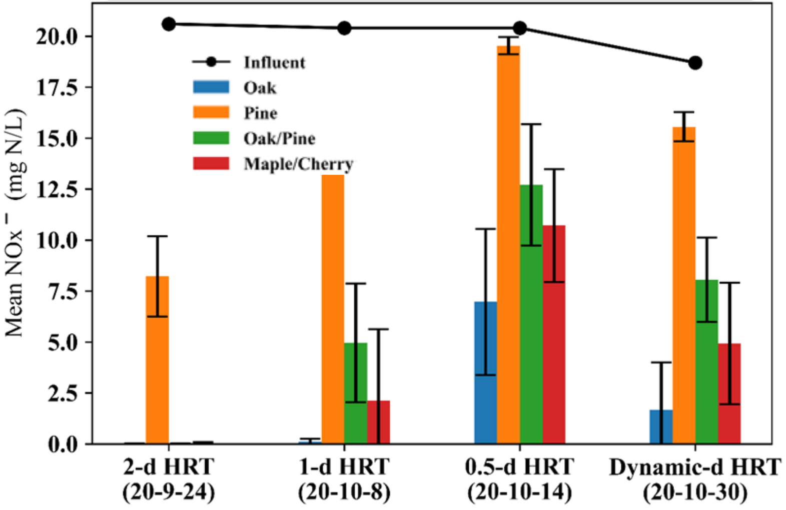
Background methane fluxes of < 50 mmol m^{-2} day^{-1} are within the range of methane fluxes from salt marshes (Al-Hay and Fulweiler 2020).



Long-term column experiment 2020-2021

Nitrate Removal

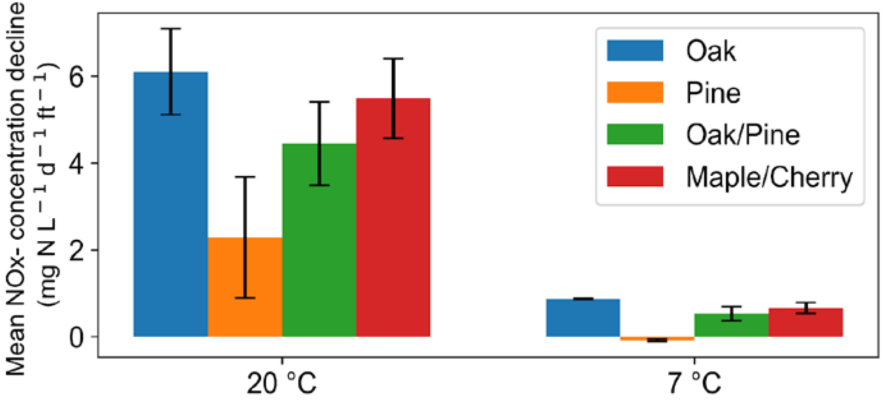
- Sustained N-removal by aged woodchips
- N-removal differs between woodchip media
- Effluent nitrate scales with HRT



~2 ft d^{-1} ~4 ft d^{-1} ~8 ft d^{-1} ~4 ft d^{-1}

Adequate PRB thickness – temp. dependance

- Nitrate concentration decline: 4.5-6 mg L^{-1} per ft of hardwood media at summer temperatures.
- Ideal PRB thickness can be modeled.



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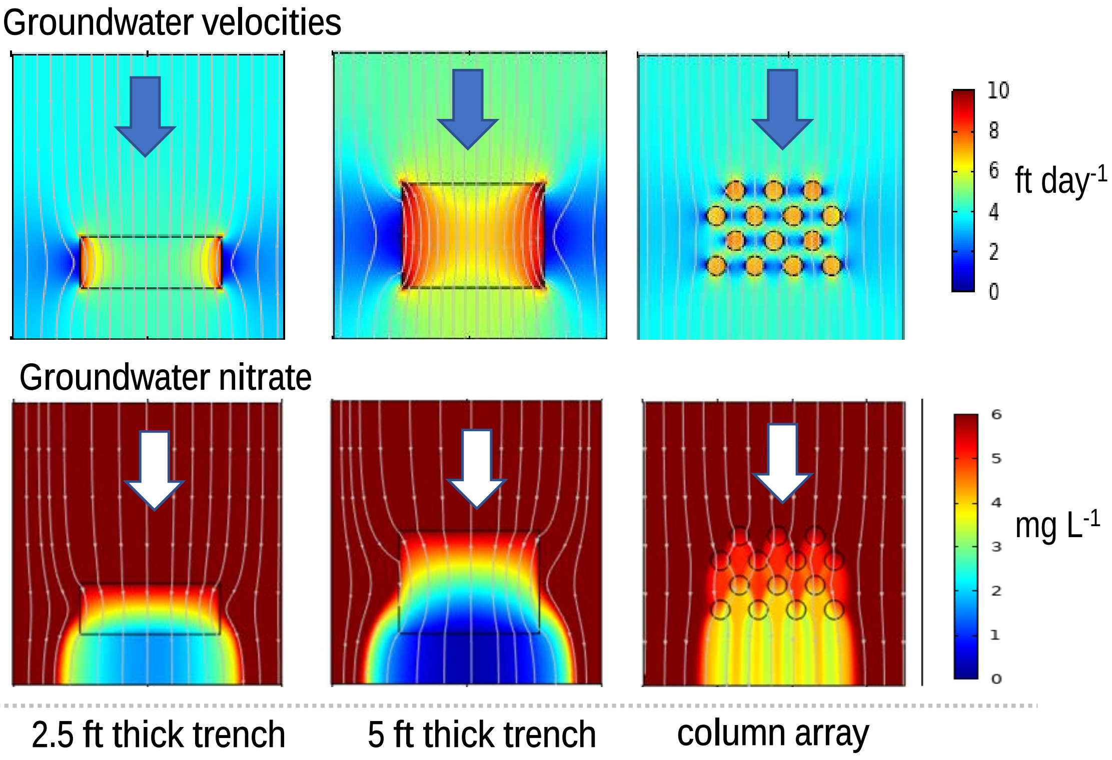
Model Simulations of different PRB designs

- Informed by laboratory experiments and measurements (biogeochemical rates, matrix properties)
- Informed by site-specific hydrological settings (groundwater velocities, soil hydraulic conductivity)
- Validation by performance monitoring of in-ground systems

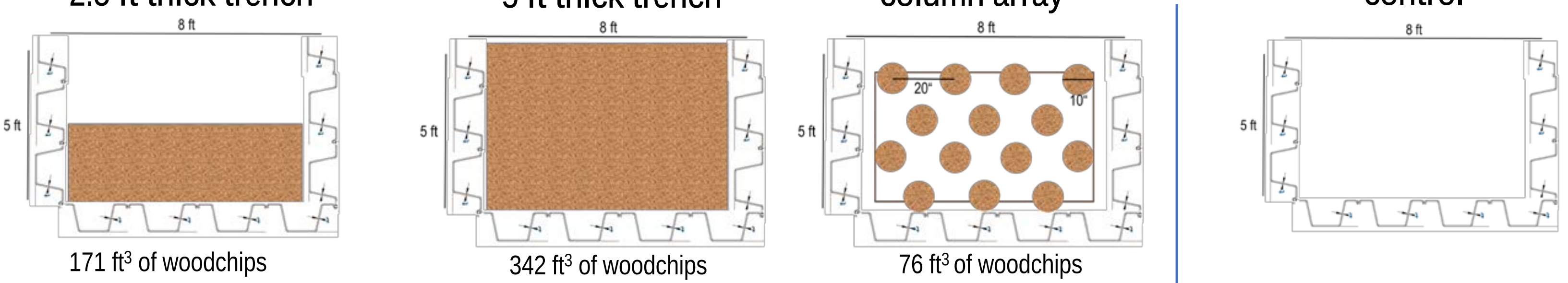


PRB installation: test cells behind a marine bulkhead at Hampton Bays (in collaboration with CCE)

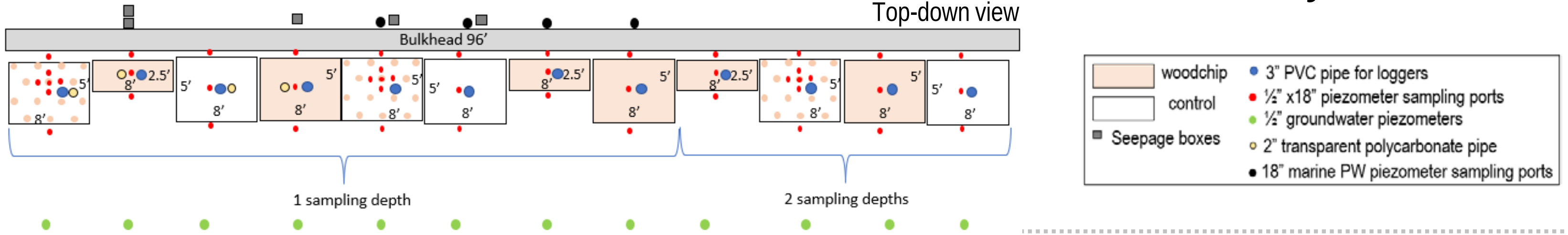
Testing different PRB designs

Funding: CPF Town of Southampton, Hampton Hills Association

Based on O_2 penetration and N-removal data and modelling we predicted that a 2.5 ft thick trench PRB would be optimal for the Hampton Bays site (close to complete N-removal in summer; minimal methane prodiction).



Each PRB type in triplicates in randomized block design



PRB installation: test cells behind a marine bulkhead at Hampton Bays (in collaboration with CCE)

Testing different PRB designs

Installation in September 2020

Bulkhead sheet perforated belowground

Column-type PRB

2.5 and 5 ft trench-type PRB

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PRB installation: test cells behind a marine bulkhead at Hampton Bays (in collaboration with CCE)

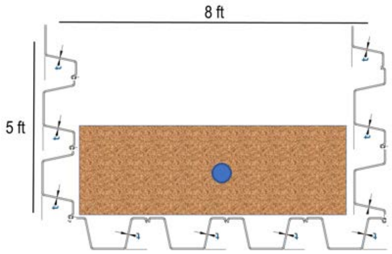
<u>Testing different PRB designs</u>

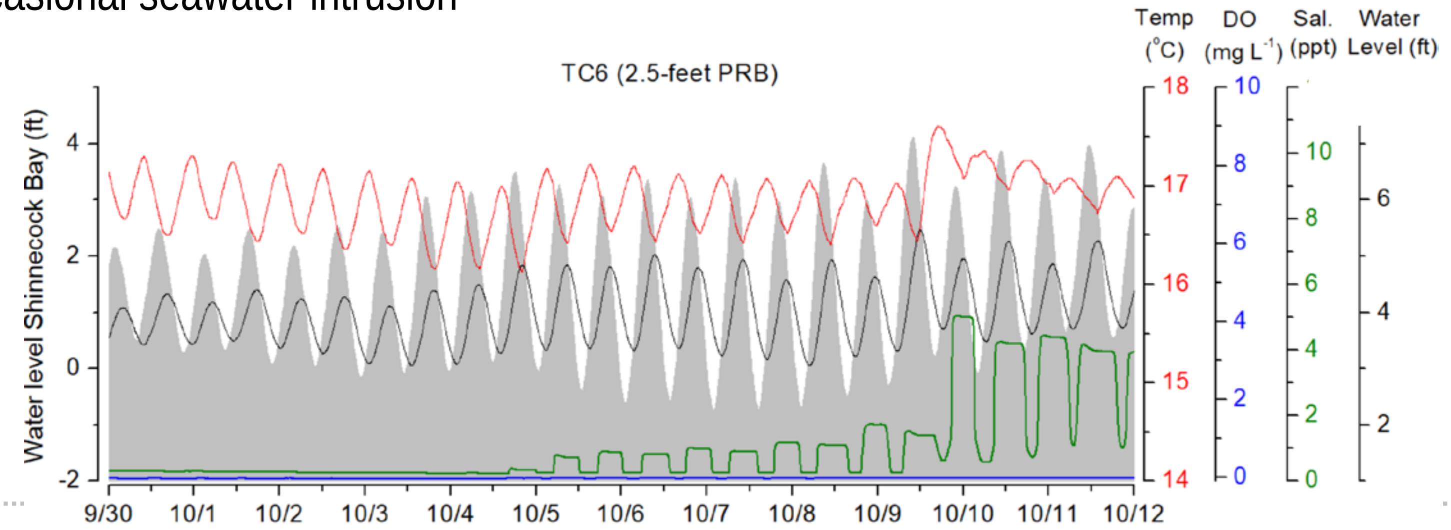
First sampling campaign in April 2020

PRB installation: test cells behind a marine bulkhead at Hampton Bays (in collaboration with CCE)

Hydrobiogeochemical dynamics in test cells:

- Slightly delayed and damped tidal amplitude (4 ft in bay, 2 ft in test cells)
- **Continuously anoxic** conditions in PRB center (2.5ft and 5 ft)
- Occasional seawater intrusion





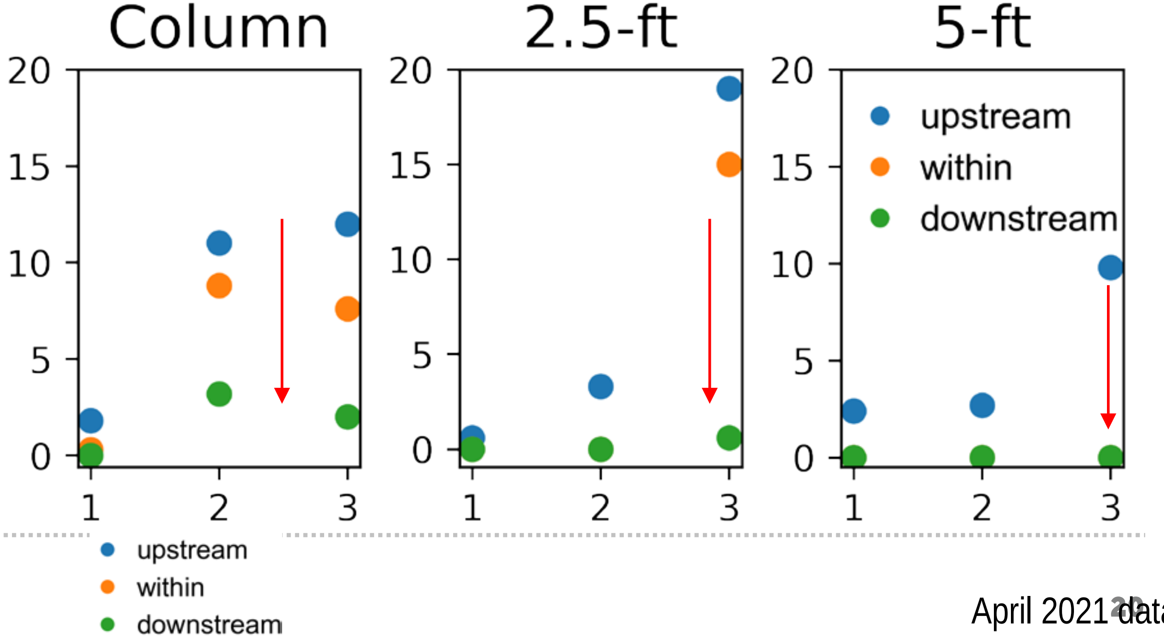
PRB installations: PRB test cells behind a marine bulkhead at Hampton Bays (in collaboration with CCE)

Nitrate Removal:

- Both trench-type test cells remove all incoming nitrate.
- Column-type test cells remove most of the incoming nitrate.
- No nitrate removal in control cells.

Next steps:

- Continue seasonal monitoring
- Formation and fate of secondary products (methane, dissolved iron)
- Performance over the tidal cycle



April 2021 data

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Other existing and upcoming PRB pilot installations:

- **Georgica Pond** Carbon Array (groundwater flow dictated by open and closing of the pond)
- **Accabonac Harbor**: Dual-zone PRBs to treat groundwater dominated by ammonia, not nitrate: Oxygen injection, Oxygen Releasing Compounds
- Comprehensive site-investigation at **Shirley Beach** to decide which type of PRB is most suited (DEC, Town of Brookhaven)

Pending Applications

- Injection wells at **Lake Agawam** (CPF funding, Town of Southampton)

Summary

- Strategically placed PRBs are an additional tool in the toolbox to **remove legacy nitrogen** with immediate reductions of N-input to coastal waters.
- They must be **properly designed at suitable sites** to be effective.
- Based on construction costs and assuming a 20+year lifetime of a PRB, we estimate a cost of $25 per lbs N removed, which is within the range of other mitigation strategies and likely outweighs the “costs of doing nothing”.

Outlook

- Find sites and secure funding for additional PRB installations
- Determine fate of secondary products (i.e., how much of the methane formed in PRB media will reach the atmosphere)
- Improve reaction-transport models (deep water attraction, O2 penetration, biogeochemical reaction networks)

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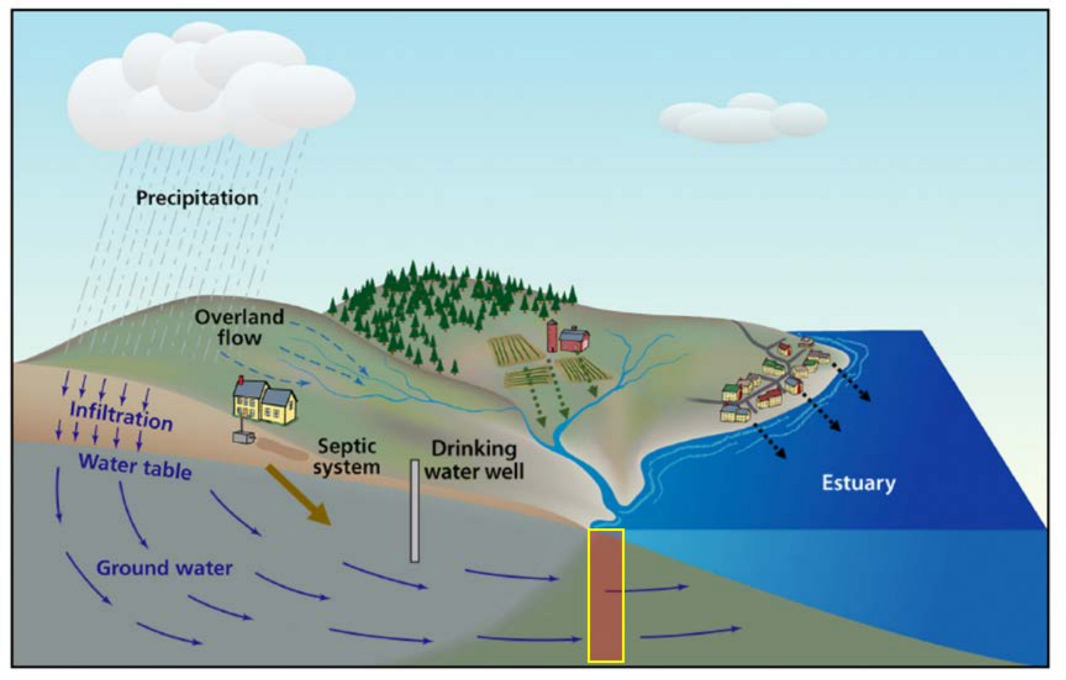
What can be done once N has been discharged to surface waters?



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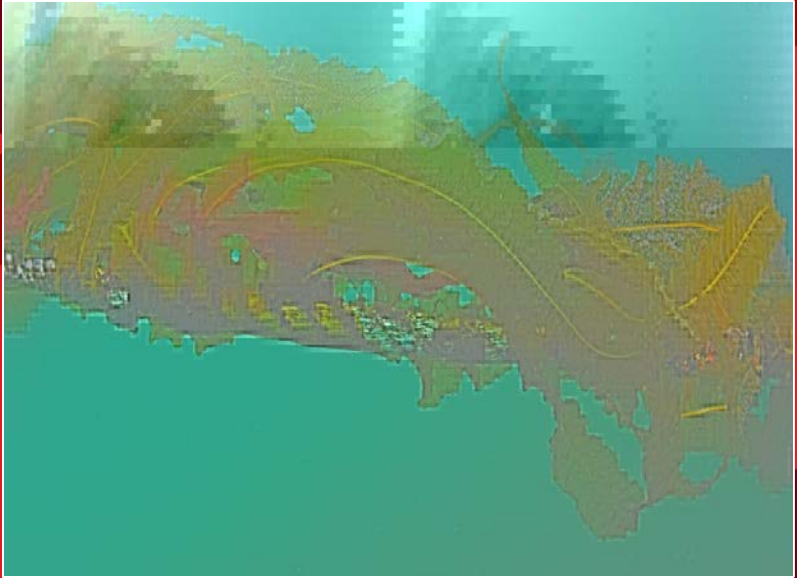
Bioextraction

Seaweeds



Bivalves

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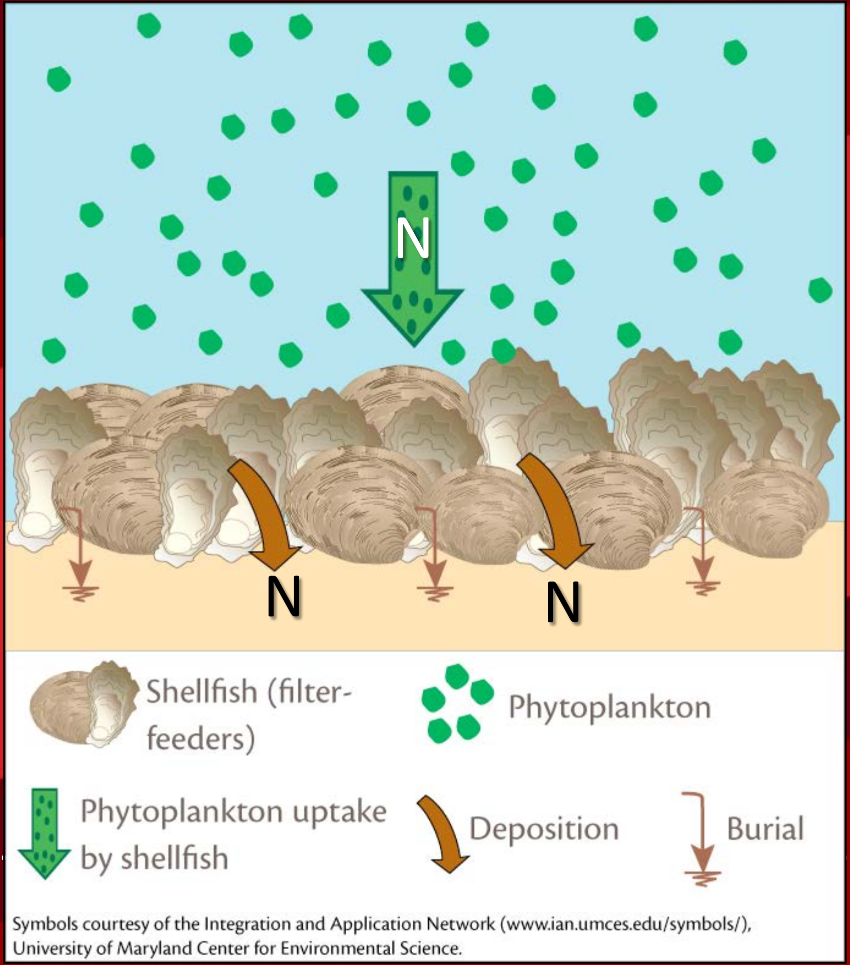
Bivalves assimilate N as they feed, turn it into new tissue, and transfer it to sediments where it may denitrify.



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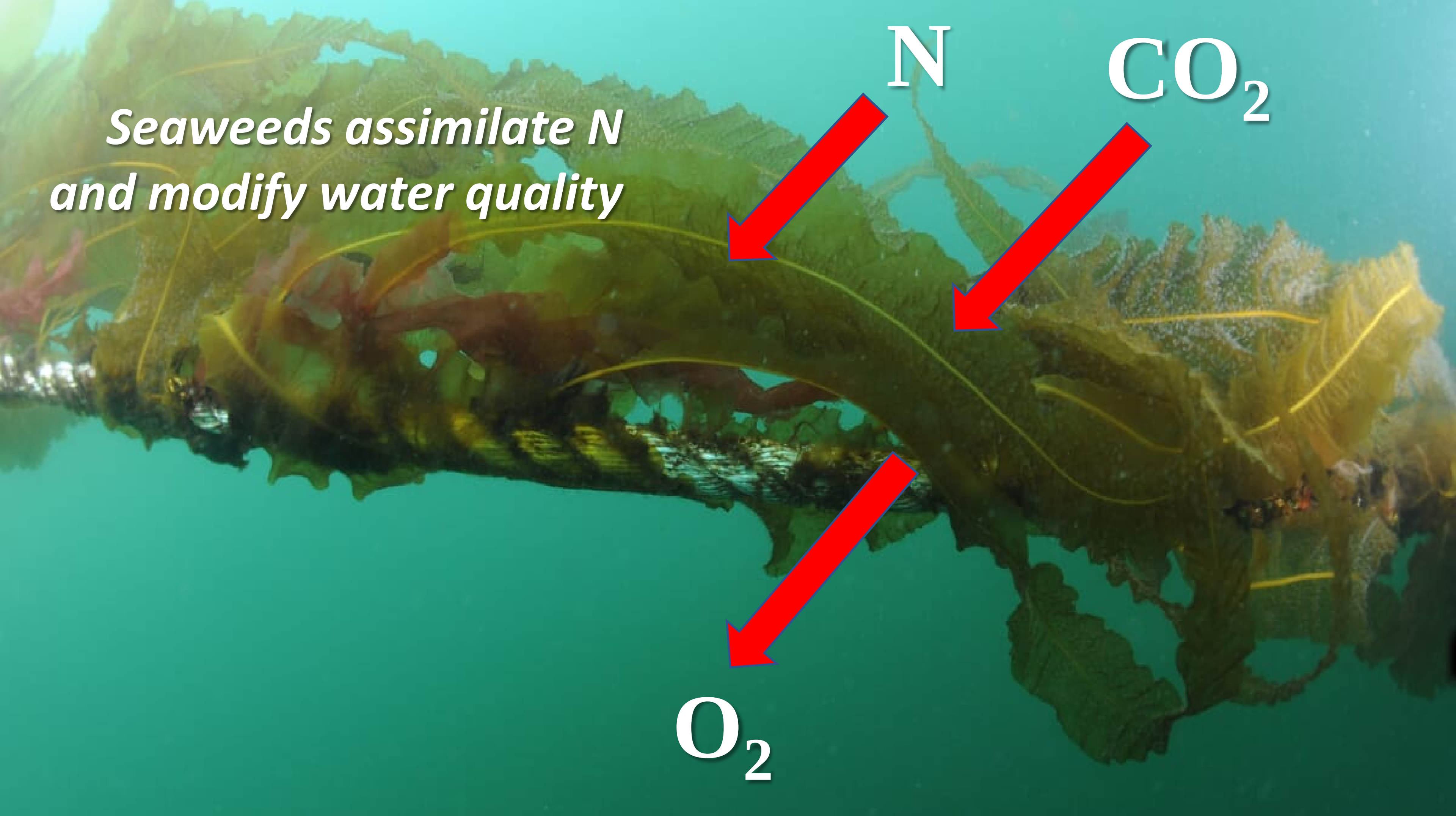


Seaweeds assimilate N and modify water quality
N
CO_2
O_2

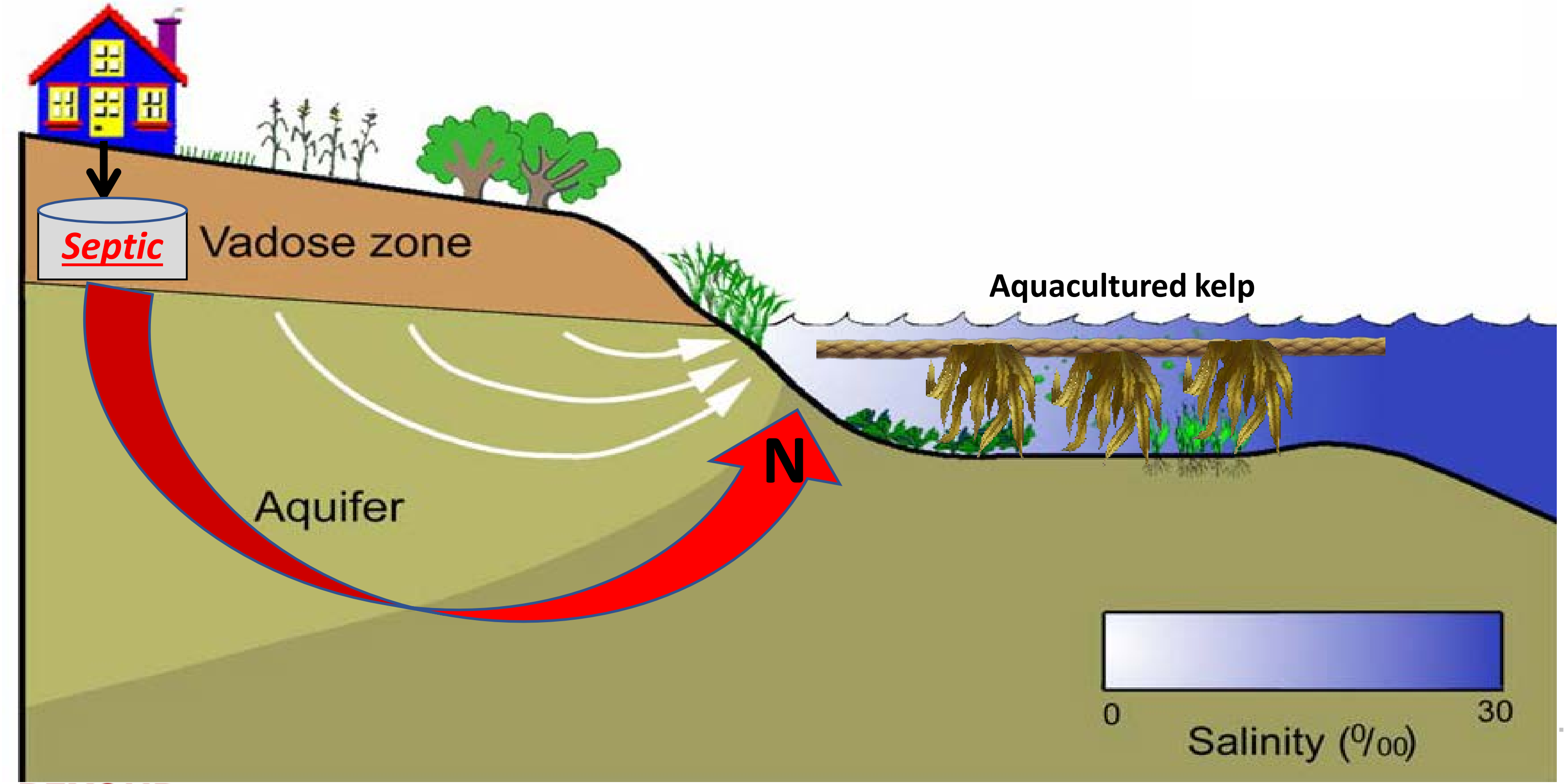
Seaweeds for all seasons

Kelp, December - May

Ulva, March - October

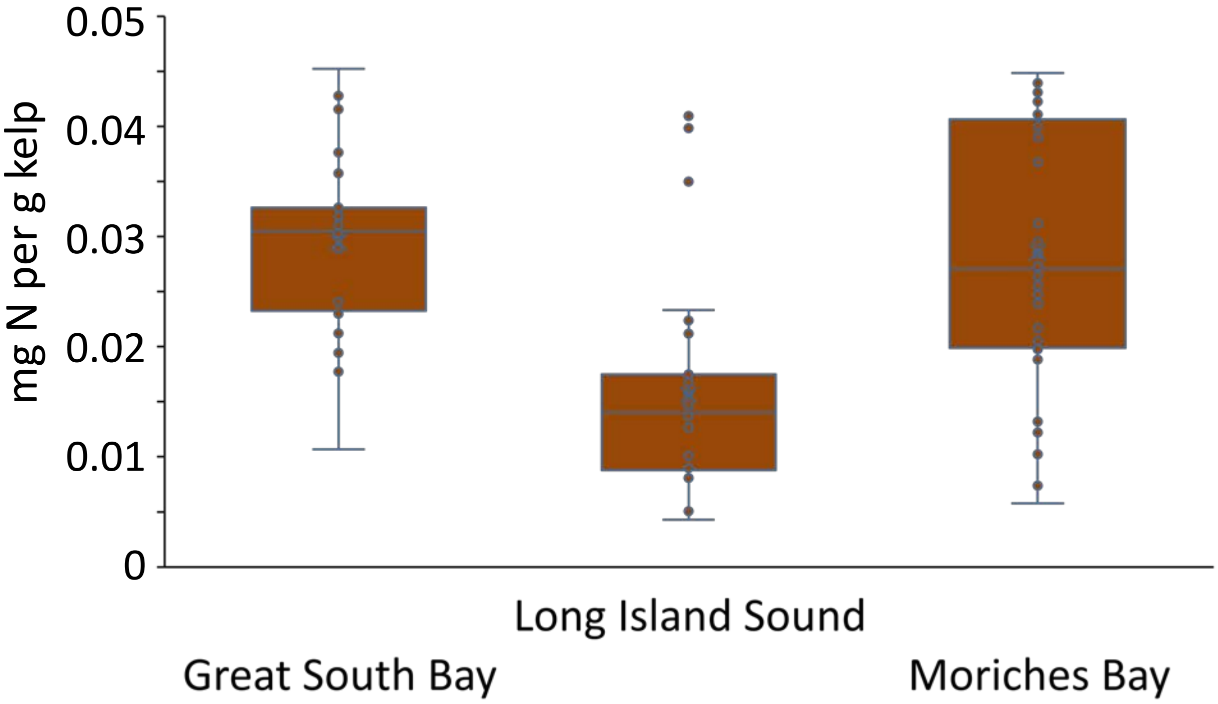
Gracilaria, June - October

Bioextraction with seaweeds: Use of seaweeds to remove N released into the environment



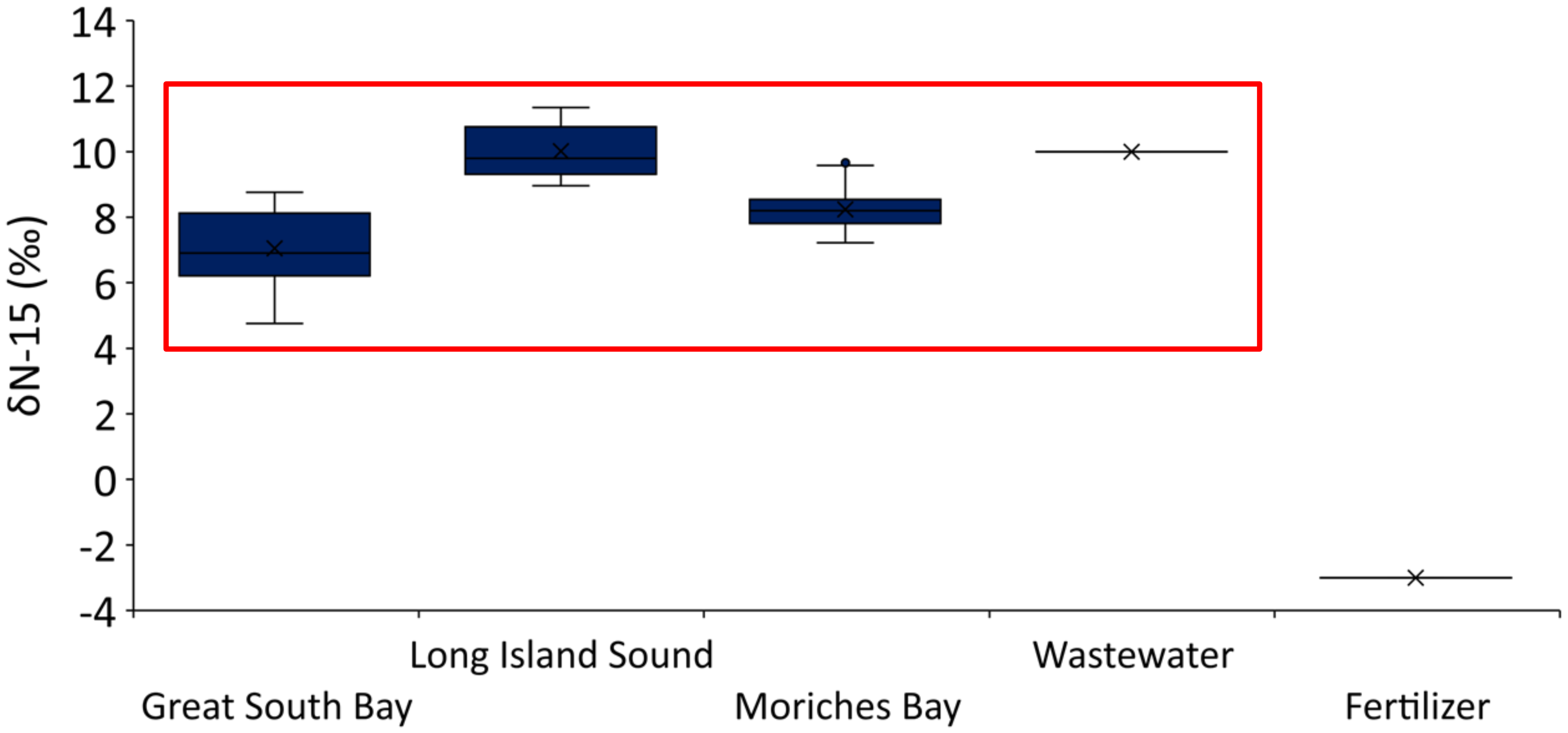
Nitrogen content of kelp per site –

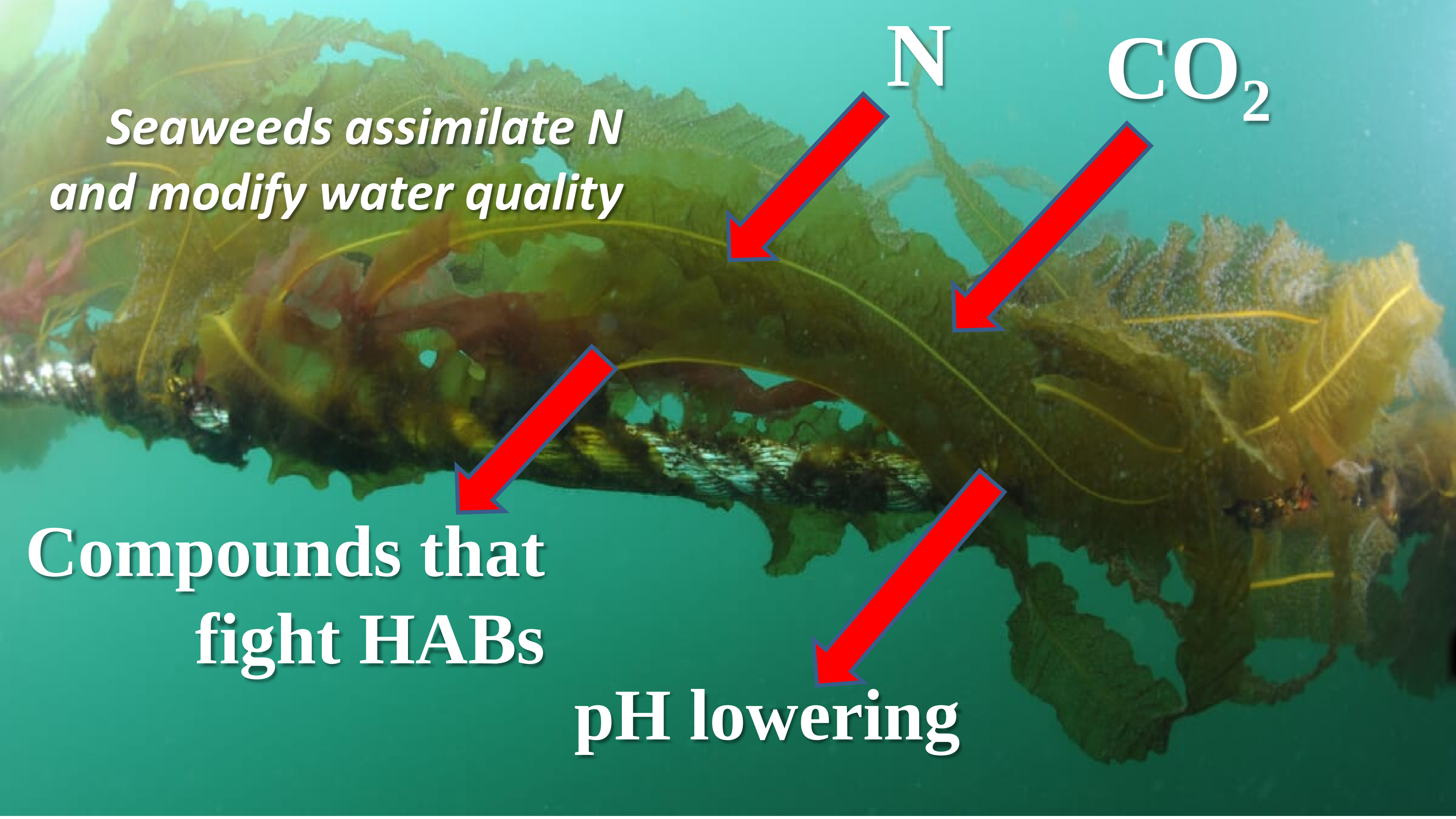
more N removed at sites with more N in the water



Tracing N sources in kelp via isotopes

- where is the N coming from?





Seaweeds assimilate N and modify water quality
N
CO_2
Compounds that fight HABs
pH lowering

Seaweeds (Kelp, *Ulva, Gracilaria, Porphyra*) improve water quality beyond N

Protect bivalves against ocean acidification

- Young, C. S., & Gobler, C. J. 2018. Biogeosciences
- Young, C. S., Sylvers, L. H., Tomasetti, S. J., Lundstrom, A., Schenone, C., Doall, M. H., & Gobler, C. J. 2022. Frontiers in Marine Science.

Combat harmful algal blooms

- Tang and Gobler, 2011, Harmful Algae
- Tang et al., 2014, Journal of Applied Phycology
- Sylvers and Gobler, 2021, Harmful Algae
- Bennitt et al., 2022, Journal of Applied Phycology

The New York Times

Account

The Johnny Appleseed of Sugar Kelp

The quest of a Long Island seaweed farmer to make kelp the next kale.

Michael Doall, Associate Director of Aquaculture and Shellfish Restoration

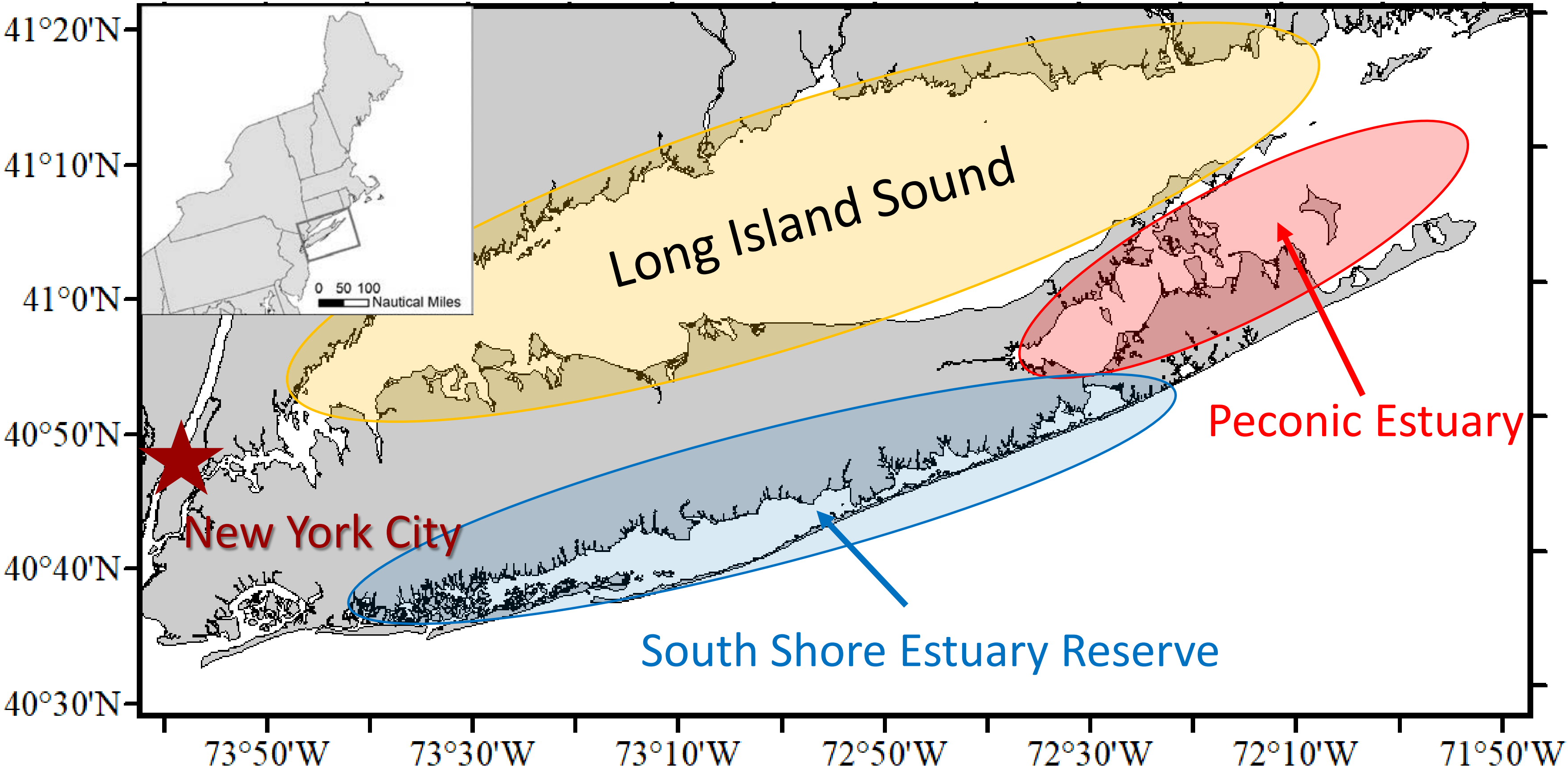
Shallow water cultivation of sugar kelp *Saccharina latissimi*: Diversifying Long Island oyster farms and getting kelp into areas most in need of nutrient bioextraction

Michael Doall*, Brooke Morrell, Tim Curtin, Christopher Gobler

School of Marine & Atmospheric Sciences, Stony Brook University

michael.doall@stonybrook.edu

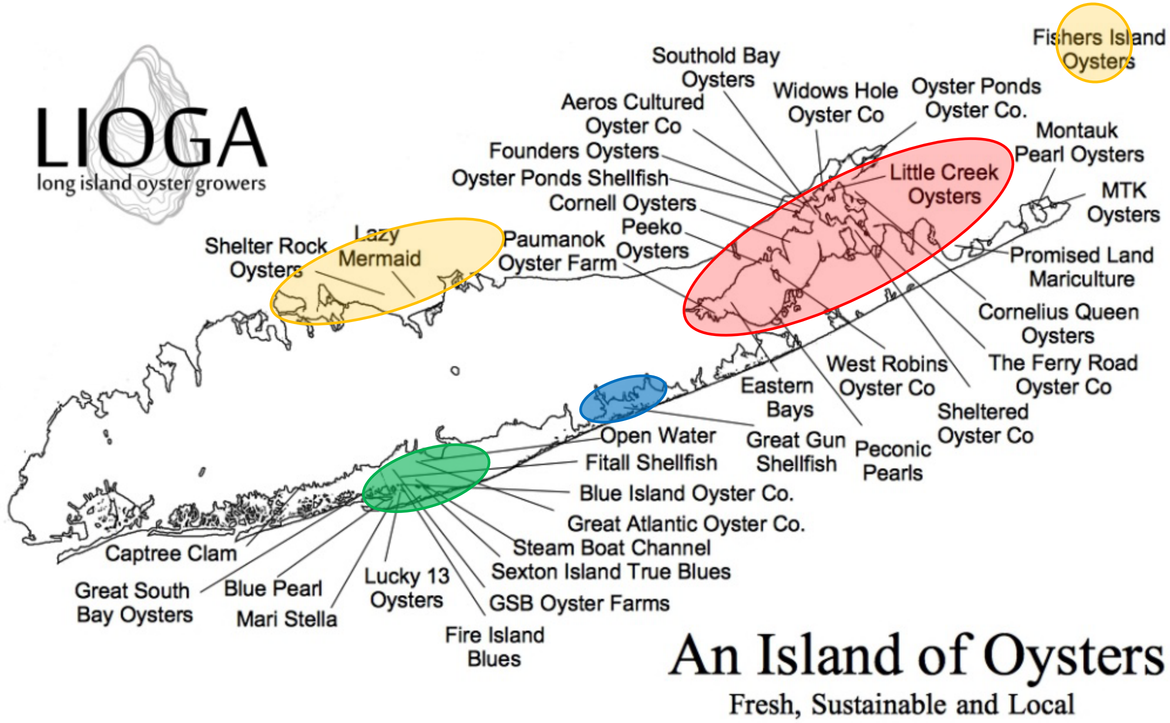
In New York, commercial mariculture is occurring in the three main estuaries surrounding Long Island



NY mariculture is one crop - Oysters

NY mariculture industry composed of small owner-operated oyster farms, less than 10 acres in size.

51 farms reported production of ~ 6 million oysters in 2019



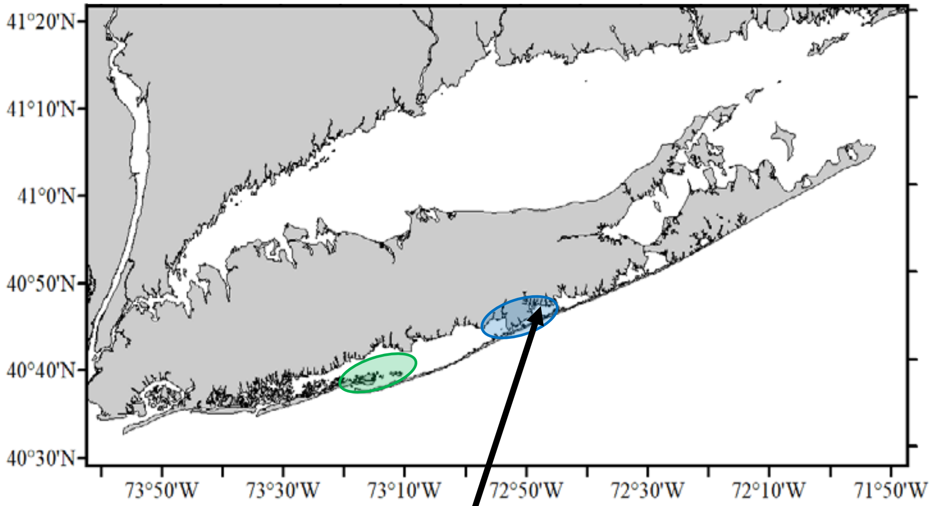
- Growing interest among NY oyster farmers in growing sugar kelp (*Saccharina latissima*) to diversify crops and create added revenue streams.

- Growing interest among NY oyster farmers in growing sugar kelp (*Saccharina latissima*) to diversify crops and create added revenue streams.

- Growing interest among coastal managers and environmental groups in using kelp farming for nutrient bioextraction to combat the negative impacts of eutrophication

Shallow water – A limitation for NY kelp farming?

- Many NY oyster farms are in shallow waters (<10 ft), particularly in the South Shore Estuary.



Shallow water – A limitation for NY kelp farming?

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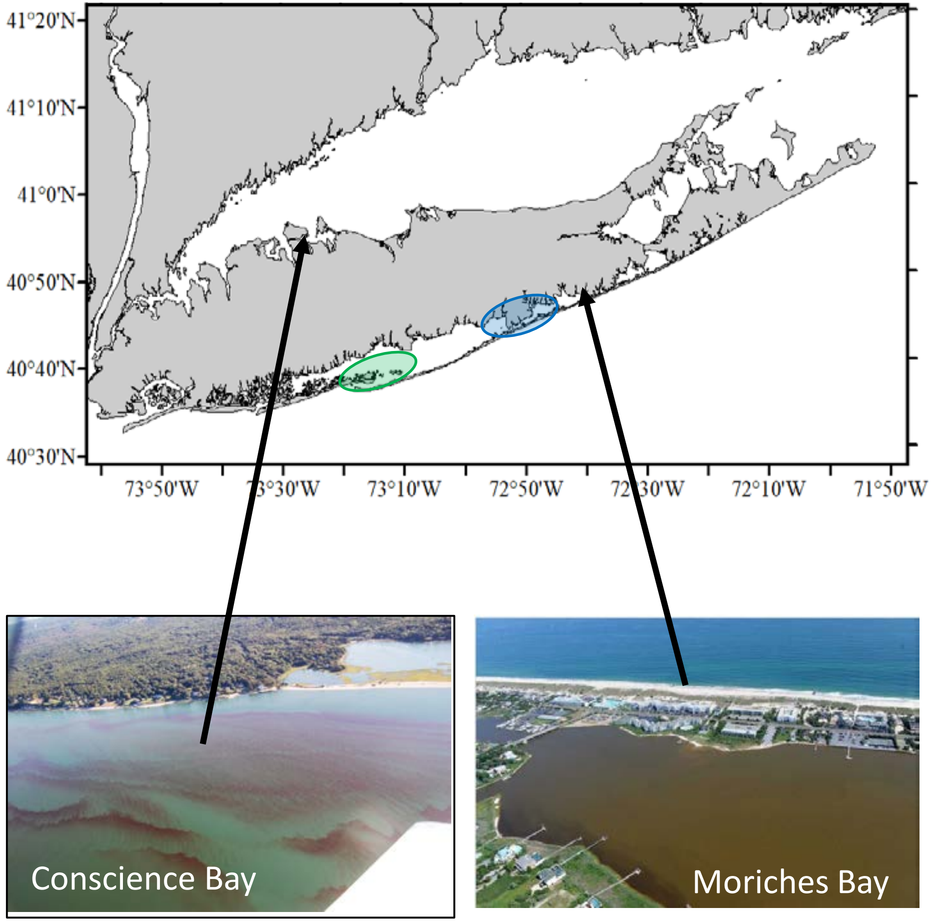
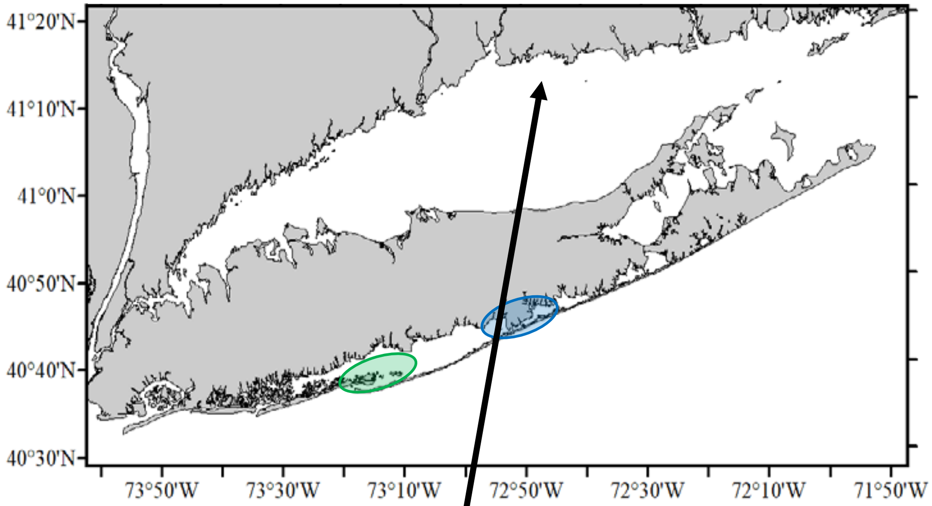
- Shallow bays often are often most impacted by eutrophication.



Shallow water – A limitation for NY kelp farming?

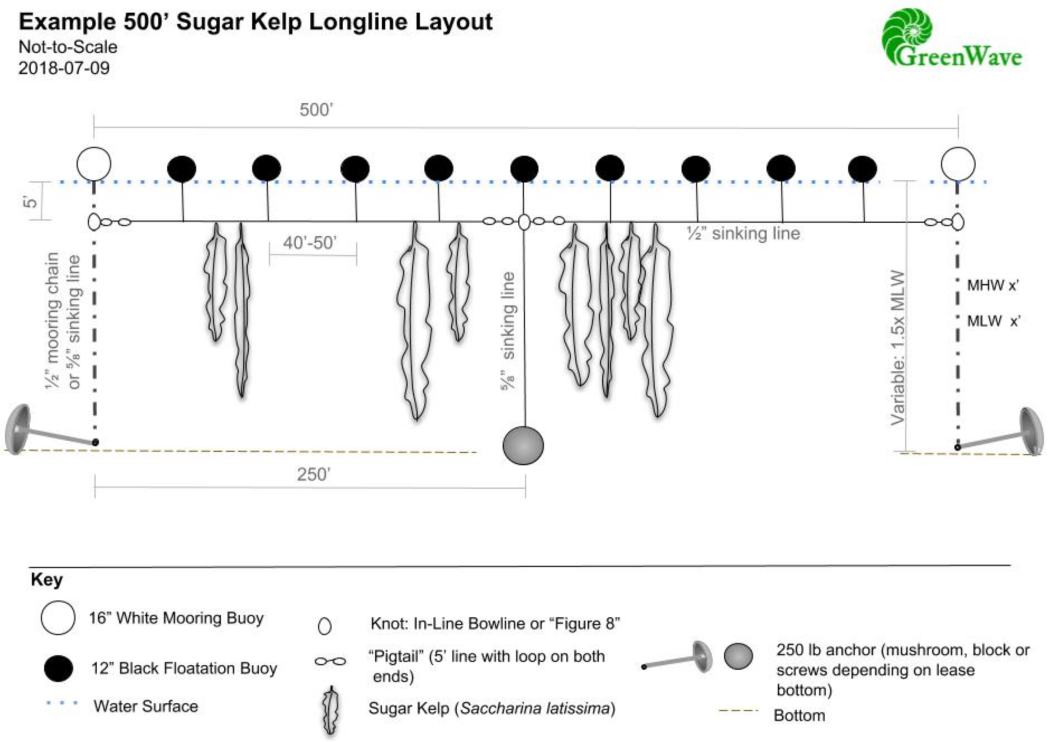
- Many NY oyster farms are in shallow waters (<10 ft), particularly in the South Shore Estuary.
- Shallow bays with low flushing are most impacted by eutrophication
- Kelp farming typically done in deep waters (>18 ft)
- Conventional wisdom is that you can't grow kelp in shallow water
  - Higher biofouling and grazing
  - Higher water temps
  - Lower growth



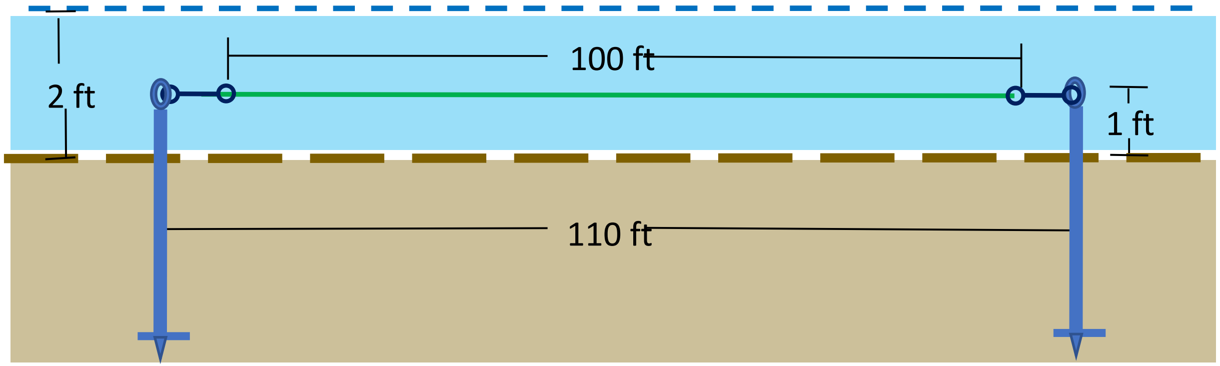
Thimble Island Ocean Farm
Photo courtesy of Greenwave

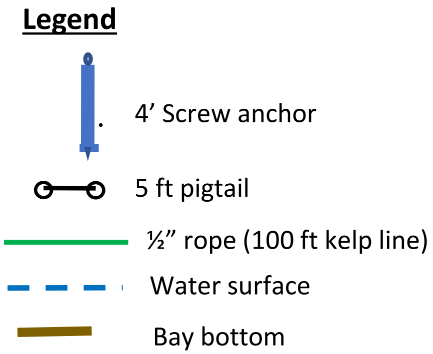
Line Installation & Seeding

Standard longline method (suspended lines)
Lines suspended a fixed distance below the surface

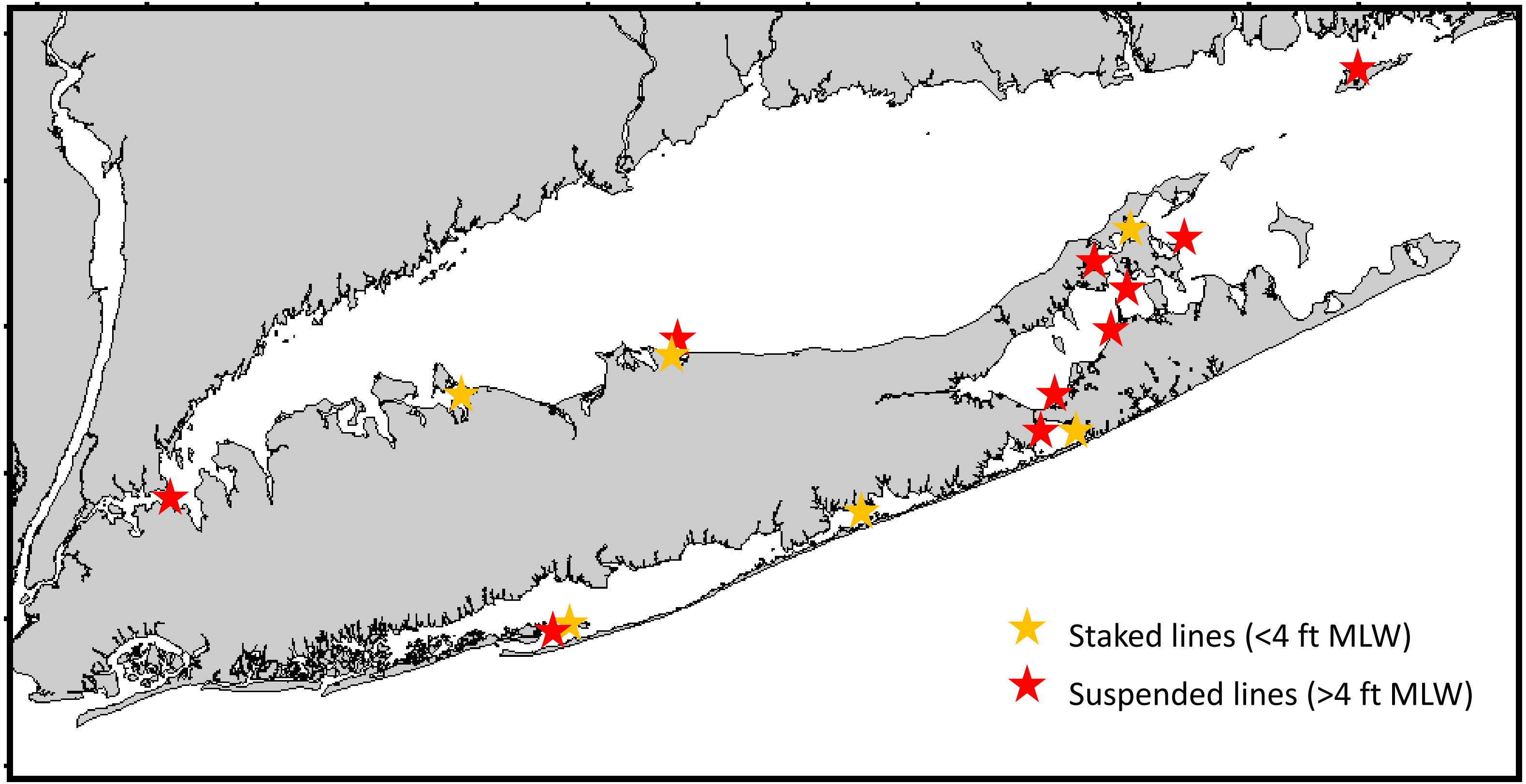


Staked line method used in waters <4 ft
Lines staked a fixed distance above the bottom



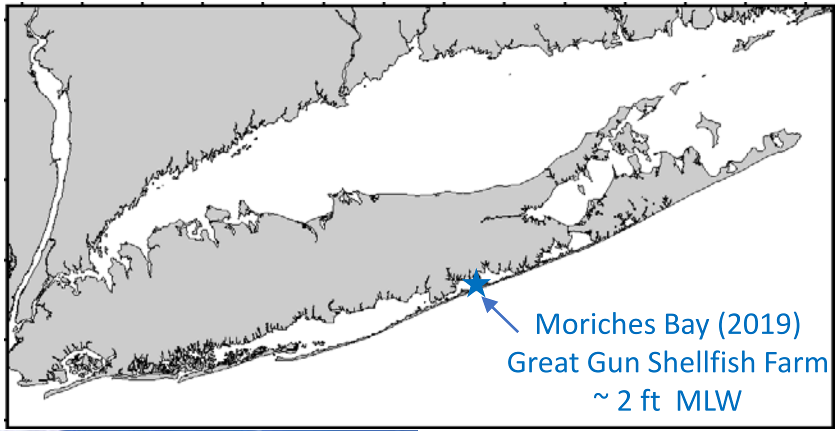


Kelp cultivation experiments at 16 locations over 4 growing seasons (2019-2022)



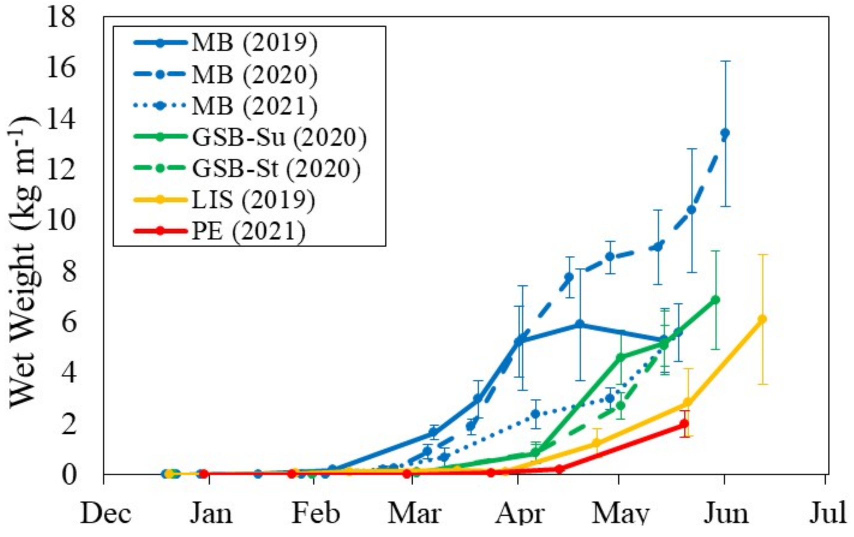
Crop Yields

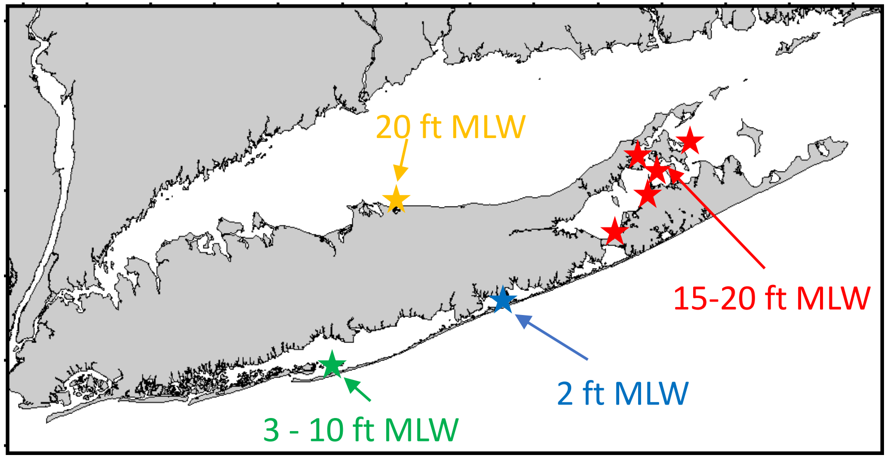
Reproducible Success in Shallow Waters



Crop Yields – Shallow vs Deep

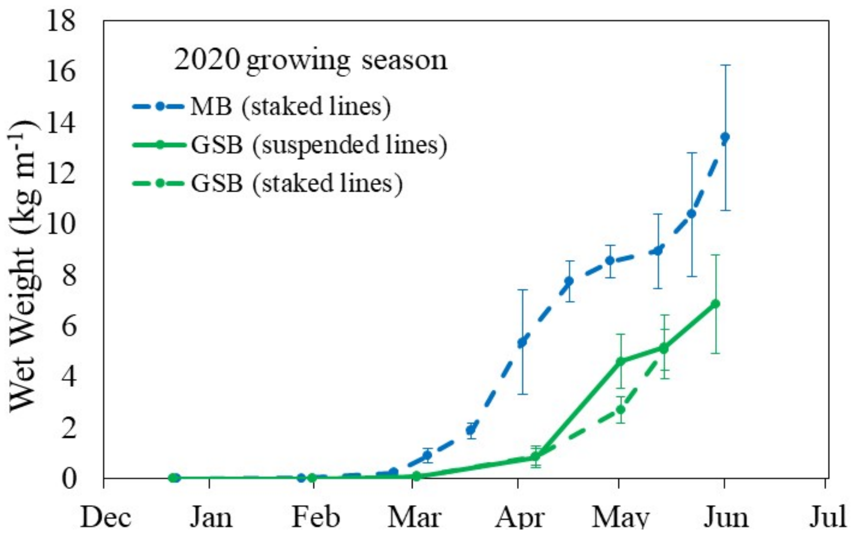
- Highest yields across sites and years in the shallowest location (2 ft MLW)
  - Line yields 9 lb ft^{-1} (13.4 kg m^{-1})
  - Kelp blades over 12 feet long
- Shallow locations had higher kelp growth early in season
- Shallow locations also experienced earlier onset of deterioration from fouling, grazing, and senescence
  - Warmer water temperature
  - Blades touching bottom

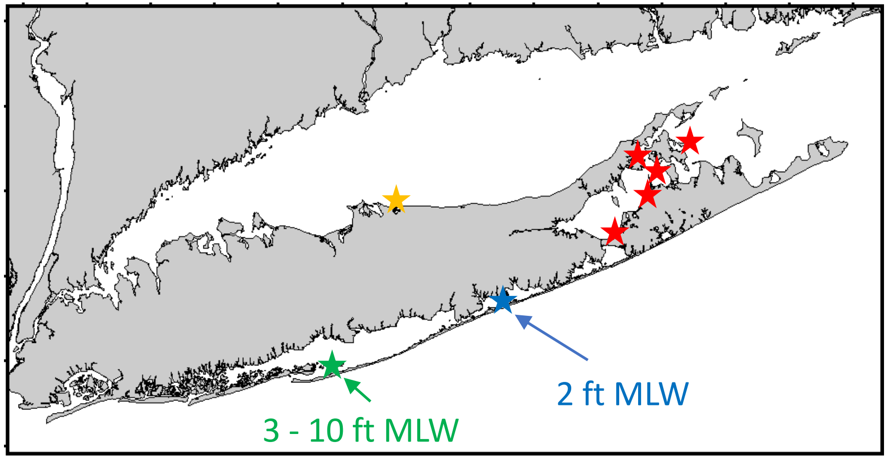




Crop Yields – Shallow vs Deep

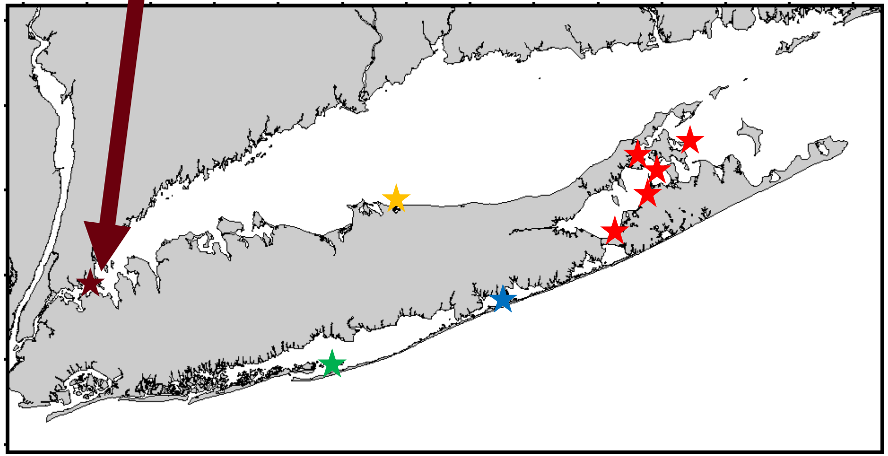
- Differences in kelp growth between sites reflect environmental differences rather than differences in cultivation method (staked vs. suspended lines)
  - Similar growth between shallow and staked lines within sites





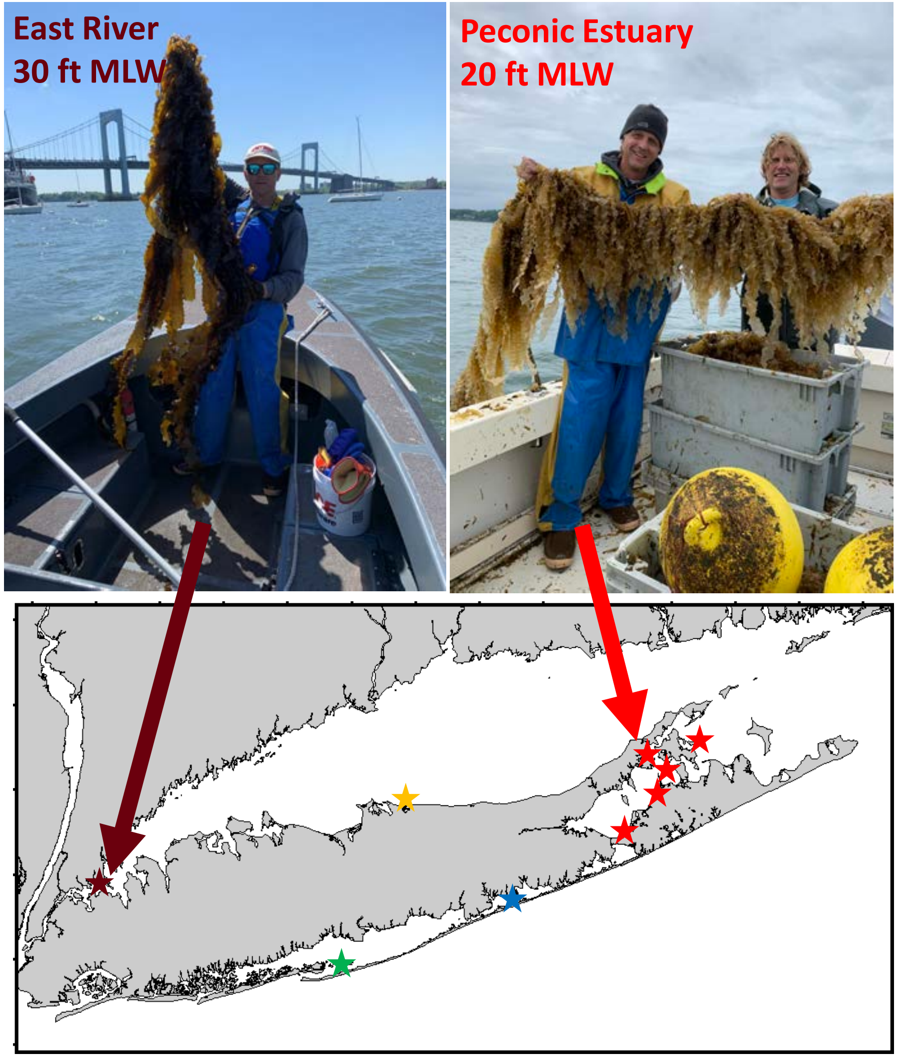
Crop Yields – Shallow vs Deep

- Differences in kelp growth between sites reflect environmental differences rather than differences in cultivation method (staked vs. suspended lines)
  - Similar growth between shallow and staked lines within sites
- Very high growth in deep water (~40 ft) in the East River in Bronx, NY



Crop Yields – Shallow vs Deep

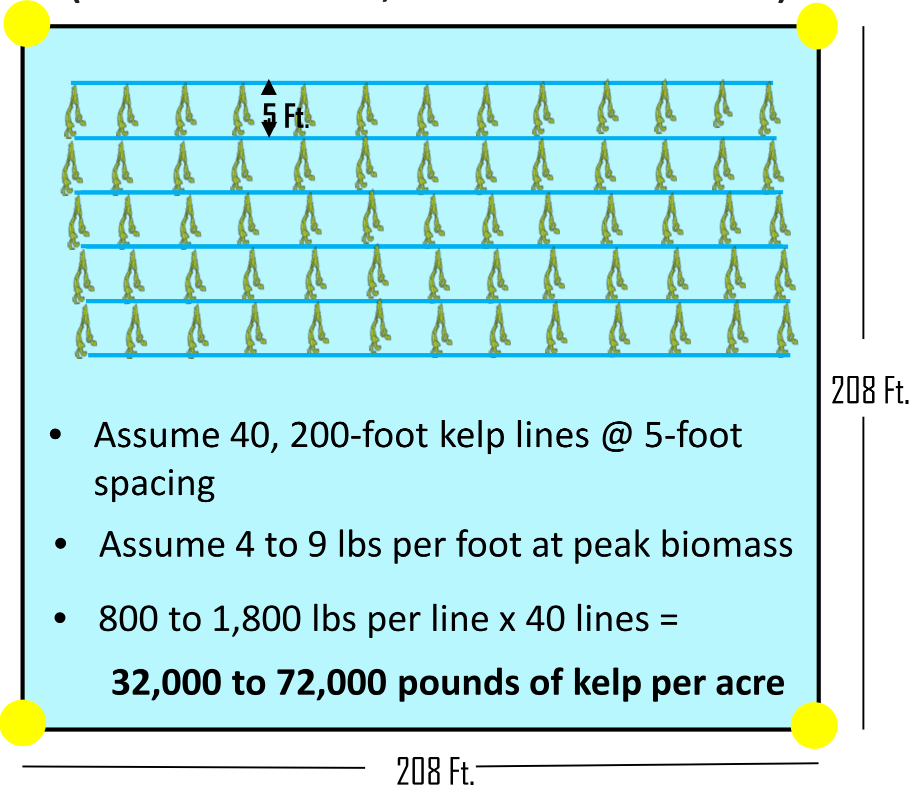
- Differences in kelp growth between sites reflect environmental differences rather than differences in cultivation method (staked vs. suspended lines)
    - Similar growth between shallow and staked lines within sites
- Very high growth in deep water (~40 ft) in the East River in Bronx, NY
- Deeper water areas with slower growth, like the Peconic Estuary, have lower nutrient levels.



Implications of shallow-water kelp farming

✓ Potential for high crop yields in areas with oyster farms and in areas most in need of nutrient bioextraction

HYPOTHETICAL ONE-ACRE SUGAR KELP FARM DESIGN IN SHALLOW WATERS (MORICHES BAY, GREAT SOUTH BAY)



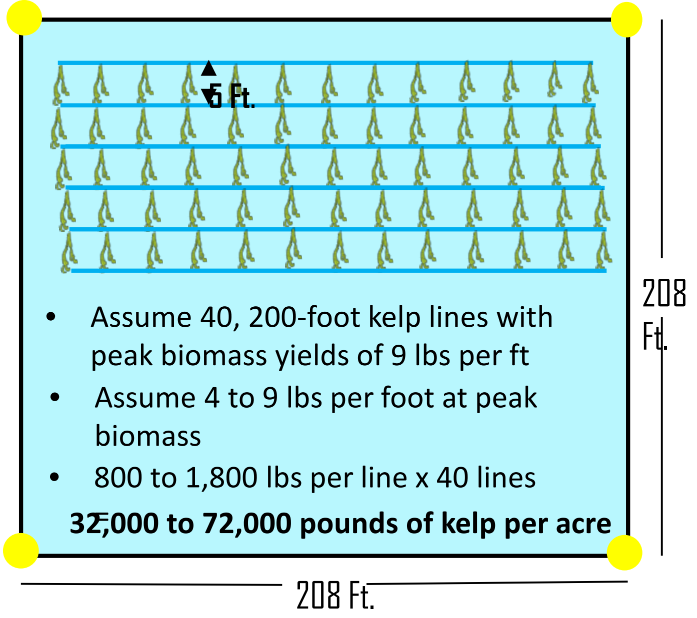
- Assume 40, 200-foot kelp lines @ 5-foot spacing
- Assume 4 to 9 lbs per foot at peak biomass
- 800 to 1,800 lbs per line x 40 lines =

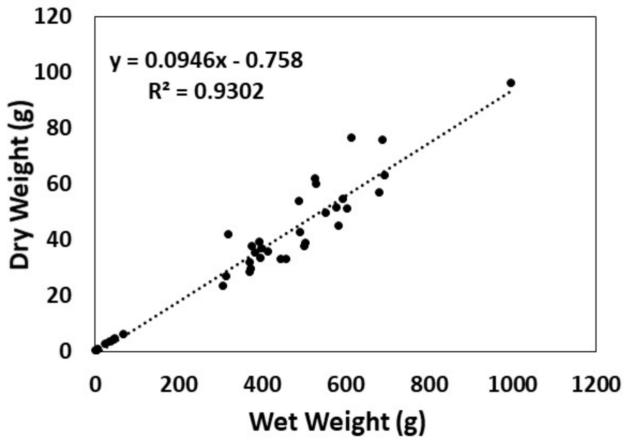
32,000 to 72,000 pounds of kelp per acre

Nutrient Bioextraction

Nitrogen Bioextraction in shallow waters (Moriches Bay, 2019-2021)

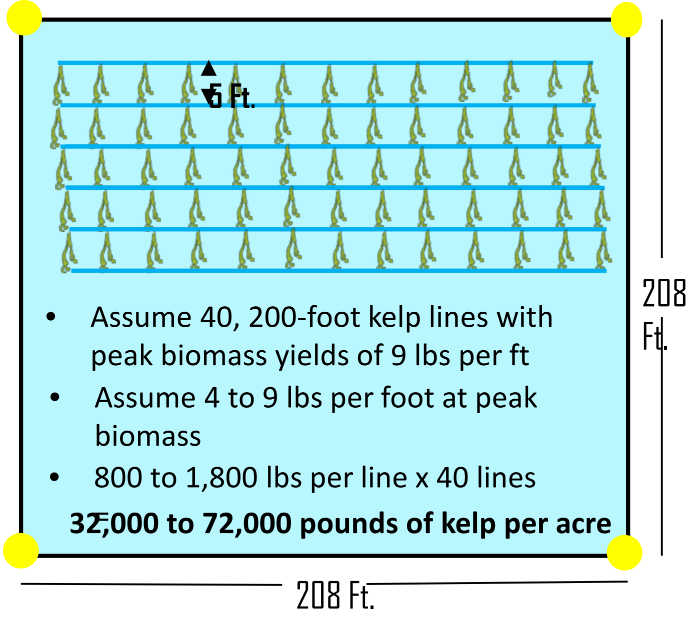
- Crop yields (fresh weight) = 32,000 to 72,000 lbs per acre
- Crop yields (dry weight) = 3,026 to 6,811 lbs per acre

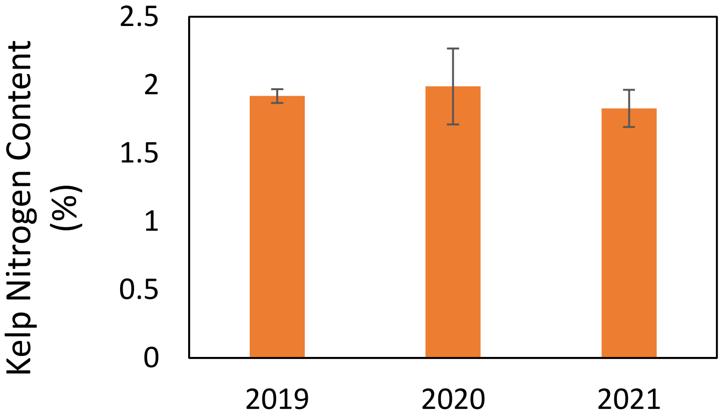




Nitrogen Bioextraction in shallow waters (Moriches Bay, 2019-2021)

- Crop yields (fresh weight) = 32,000 to 72,000 lbs per acre
- Crop yields (dry weight) = 3,026 to 6,811 lbs per acre
- Nitrogen content of kelp tissue at peak biomass = 1.83% to 1.99%





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- Nitrogen content of kelp tissue at peak biomass = 1.83% to 1.99%
- Nitrogen removed = 55.4 to 135.5 lbs N per acre
- Annual nitrogen removal equivalent to 5 to 11 innovative/alternative septic systems

Acknowledgements

Collaborators:

- Greenwave
- Gobler Lab
- Partner oyster farms

Funding from:

- USDA Specialty Crop Block Grant Program / New York Farm Viability Institute
- New York Sea Grant
- Suffolk County
- Long Island Sound Study
- NYSDEC


Thank you!