Mitigating nitrogen beyond the source with reactive barriers and bioextraction

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Treatment of Legacy Groundwater Nitrogen with Permeable Reactive Barriers to Mitigate Coastal Ocean Eutrophication
Water Quality Improvement Project (WQIP) Program

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FAR BEYOND
The problem: “Legacy Nitrogen”

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

Modified from: Jack Cook, WHOI

Groundwater Travel Times

“All of Long Island is a watershed”

Misut and Monti 2016
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
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)

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**Trench-type PRBs**

**Funnel-and-Gate PRBs**

**Column Arrays and Injection Wells**

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)
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
Nitrate Removal

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

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

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

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).

Pollution swapping!
Nitrate Removal

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

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.
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

**Groundwater velocities**

**Groundwater nitrate**

- 2.5 ft thick trench
- 5 ft thick trench
- Column array
Testing different PRB designs

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 production).

- **2.5 ft thick trench**
  - 171 ft$^3$ of woodchips

- **5 ft thick trench**
  - 342 ft$^3$ of woodchips

- **Column array**
  - 76 ft$^3$ of woodchips

- **Control**

Each PRB type in triplicates in randomized block design

Groundwater flow

**Funding:** CPF Town of Southampton, Hampton Hills Association
Testing different PRB designs
Installation in September 2020

- Bulkhead sheet perforated belowground
- Column-type PRB
- 2.5 and 5 ft trench-type PRB

PRB installation: test cells behind a marine bulkhead at Hampton Bays (in collaboration with CCE)
Testing different PRB designs
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
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
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)
What can be done once N has been discharged to surface waters?
Bioextraction

Seaweeds

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

[Diagram showing box plots for Nitrogen content per g of kelp in Long Island Sound, Great South Bay, and Moriches Bay.]
Tracing N sources in kelp via isotopes
- where is the N coming from?
Seaweeds assimilate N and modify water quality. Compounds that fight HABs. pH lowering.
Seaweeds (Kelp, Ulva, Gracilaria, Porphyra) improve water quality beyond N

Protect bivalves against ocean acidification


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 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

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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.
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• 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.
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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
Line Installation & Seeding
Standard longline method (suspended lines)
Lines suspended a fixed distance below the surface

Example 500' Sugar Kelp Longline Layout
Not-to-Scale
2018-07-09

Key
- 16" White Mooring Buoy
- 12" Black Floatation Buoy
- Water Surface
- Knot: In-Line Bowline or “Figure 8”
- “Pigtails” (5' line with loop on both ends)
- Sugar Kelp (Saccharina latissima)
- 250 lb anchor (mushroom, block or screws depending on lease bottom)
- Bottom
Staked line method used in waters <4 ft
Lines staked a fixed distance above the bottom

Legend
- 4’ Screw anchor
- 5 ft pigtail
- ½” rope (100 ft kelp line)
- Water surface
- Bay bottom
Kelp cultivation experiments at 16 locations over 4 growing seasons (2019-2022)

- Staked lines (<4 ft MLW)
- Suspended lines (>4 ft MLW)
Crop Yields
Reproducible Success in Shallow Waters

Moriches Bay (2019)
Great Gun Shellfish Farm
~ 2 ft MLW

2019

2020

2021

2022
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
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- Very high growth in deep water (~40 ft) in the East River in Bronx, NY

Photo: Johnny Milano
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- 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 (Moriche 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

Assume 40, 200-foot kelp lines with peak biomass yields of 9 lbs per ft
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

\[ y = 0.0946x - 0.758 \]
\[ R^2 = 0.9302 \]
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- Nitrogen content of kelp tissue at peak biomass = 1.83% to 1.99%

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Kelp Nitrogen Content (%)

- 2019
- 2020
- 2021

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- Nitrogen removed = 55.4 to 135.5 lbs N per acre
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- Nitrogen removed = 55.4 to 135.5 lbs N per acre
- Annual nitrogen removal equivalent to 5 to 11 innovative/alternative septic systems
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• Suffolk County
• Long Island Sound Study
• NYSDEC
Thank you!