Holistic Shellfish Restoration for Cleaner Water

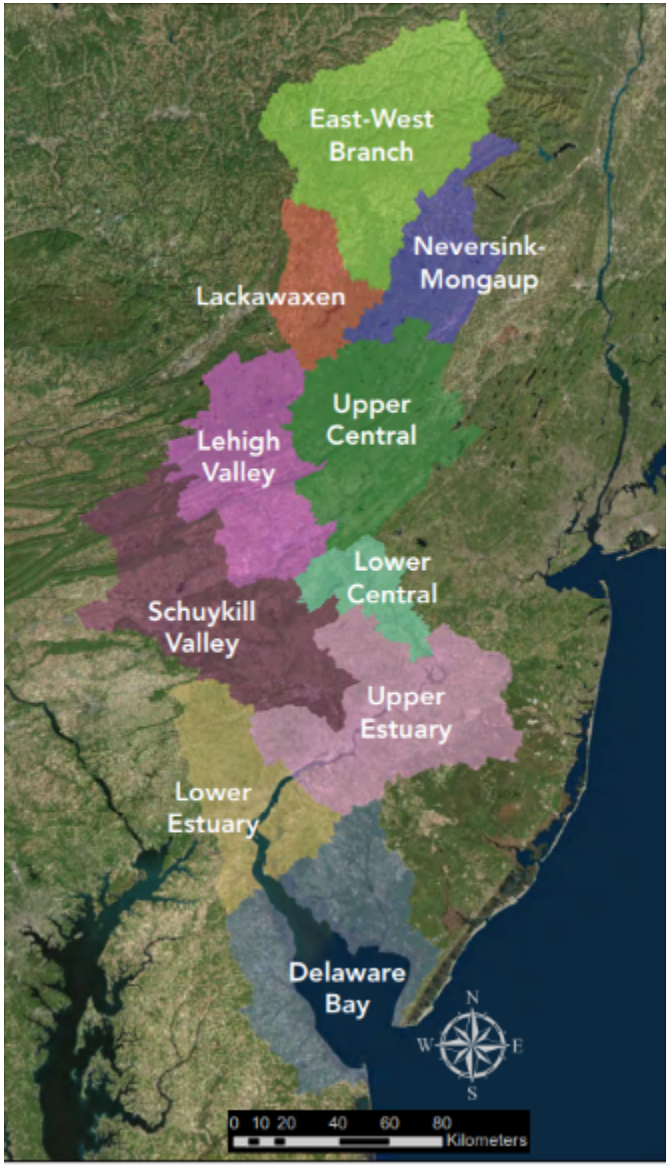
Danielle Kreeger

Partnership for the DELAWARE ESTUARY

The Partnership for the Delaware Estuary

National Estuary Program

- Fish & Wildlife
- Habitat
- Water Quantity
- Water Quality
- Communities



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Natural Capital

Guides Prioritization of Limited Resources

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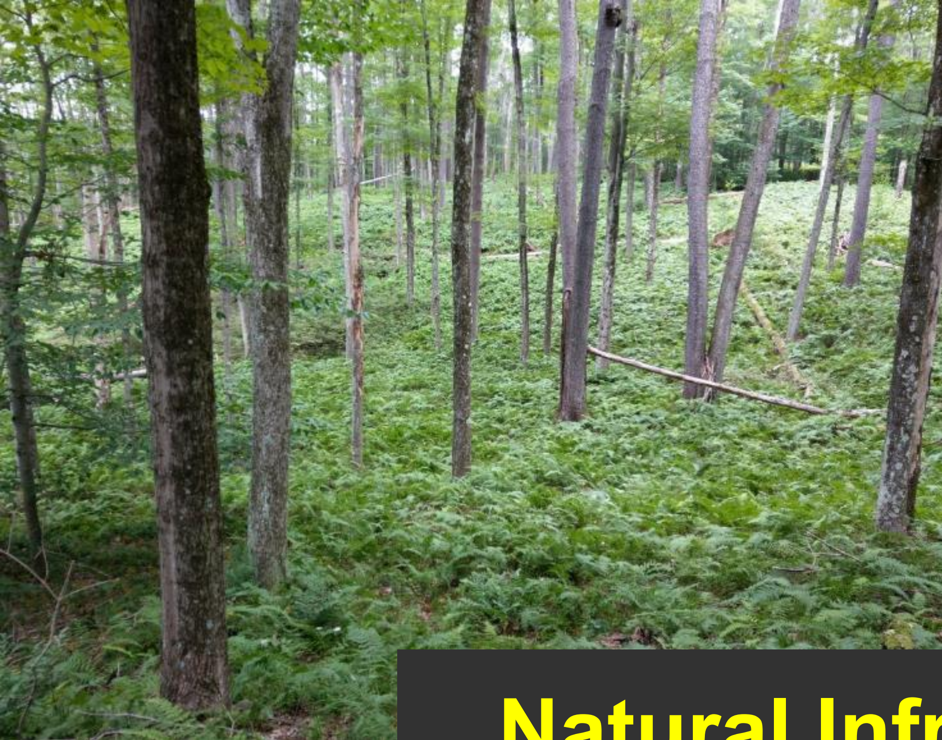
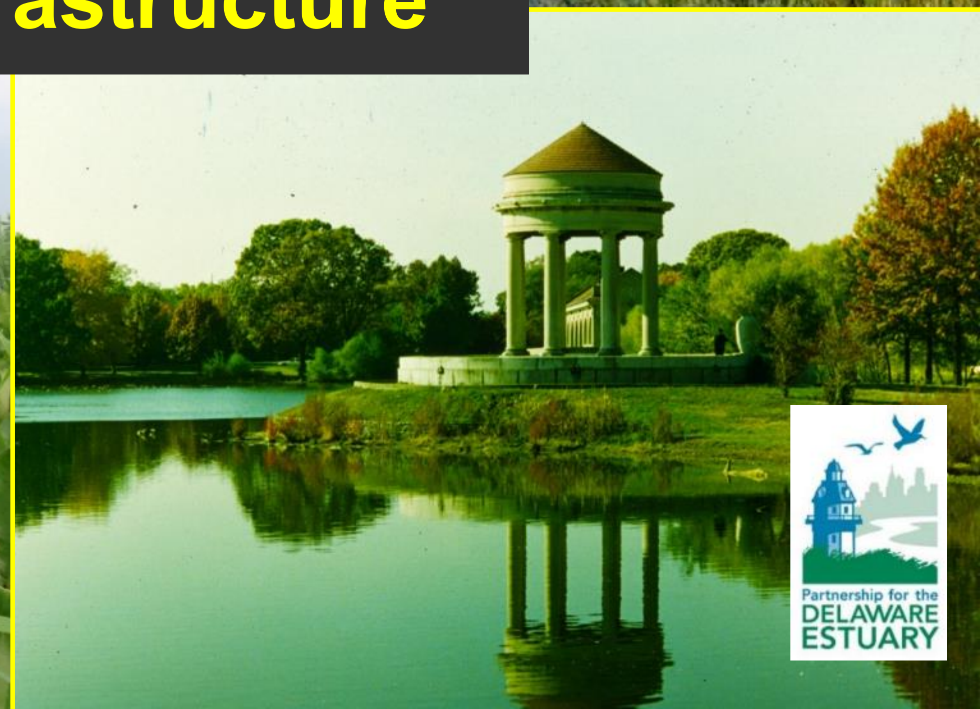


Natural Infrastructure



Foundational Habitats

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Bivalve Shellfish

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Blue Collar Bivalves

Ecosystem Engineers

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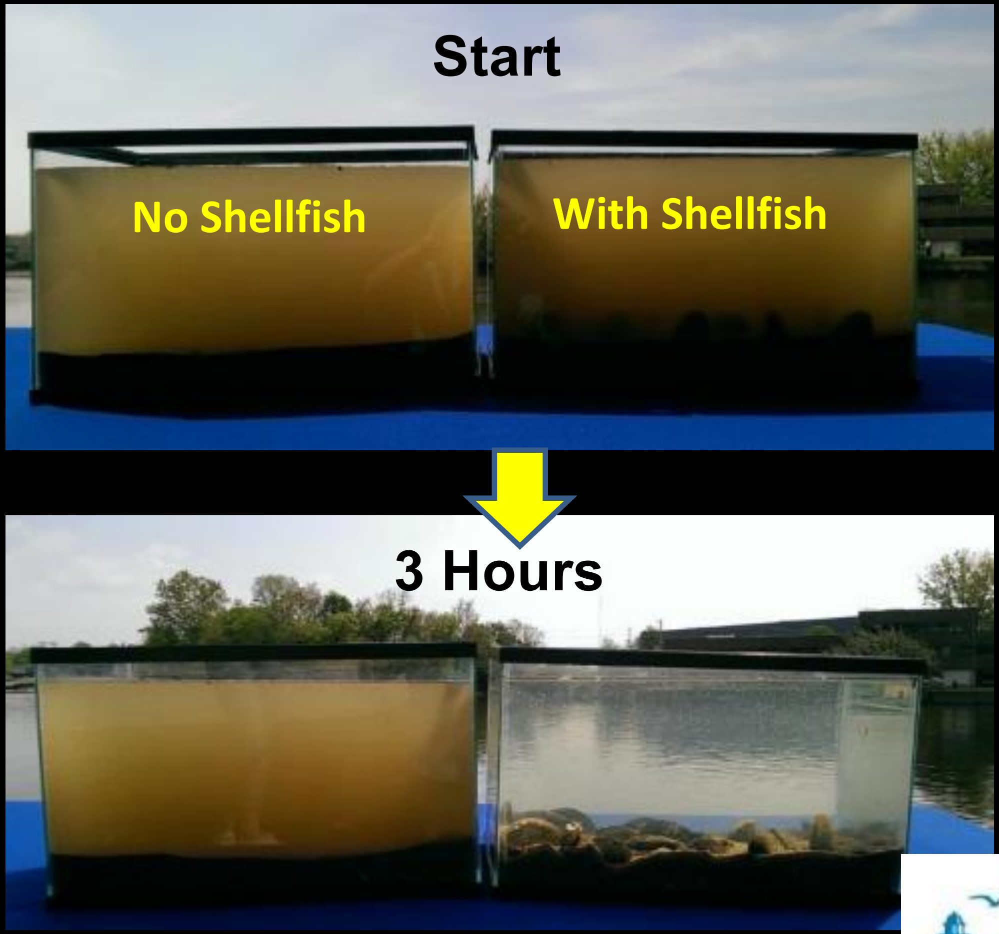
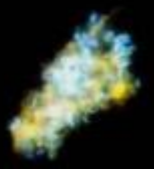
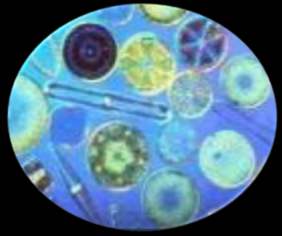
Blue Collar Bivalves

Biofiltration Services

- TSS Removal
- Nutrient Removal & Transformation
- Pathogens?







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>60 Bivalve Species



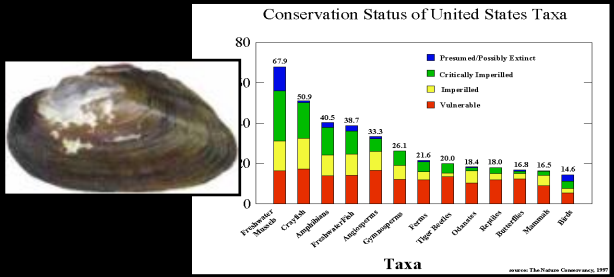




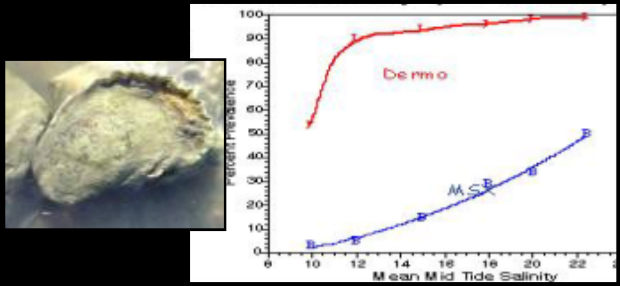



Why Mussels?

Bivalve Population Declines



Freshwater Mussels: most imperiled



Oysters: prone to disease and salinity

Ribbed Mussels: losing marsh habitat

Which Species is Best?

Which Tactic is Best?

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Species Comparison

- Physiological Capacity
- Population Carrying Capacity
- Ecological Barriers
- Policy Barriers
- Willingness to Pay

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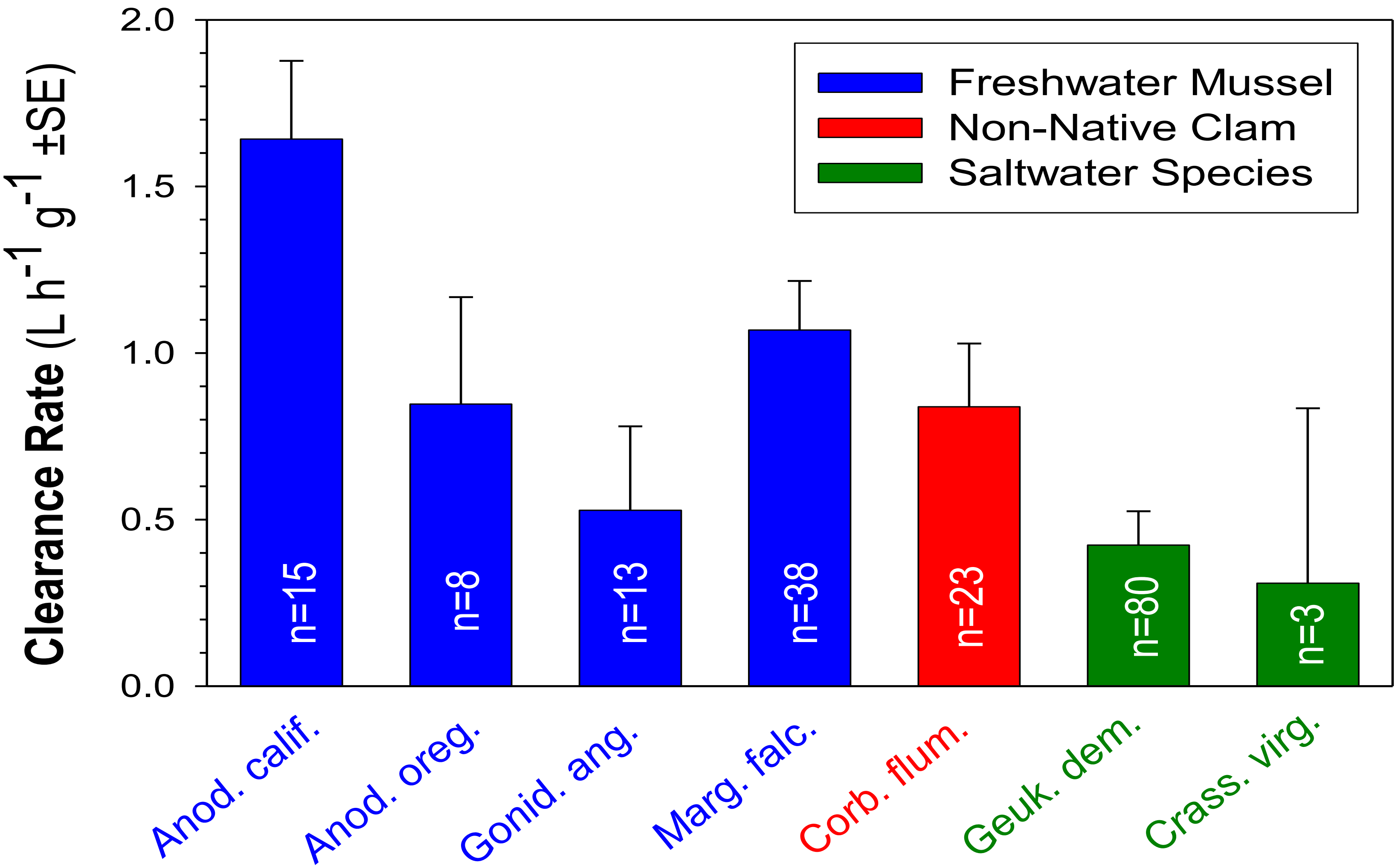
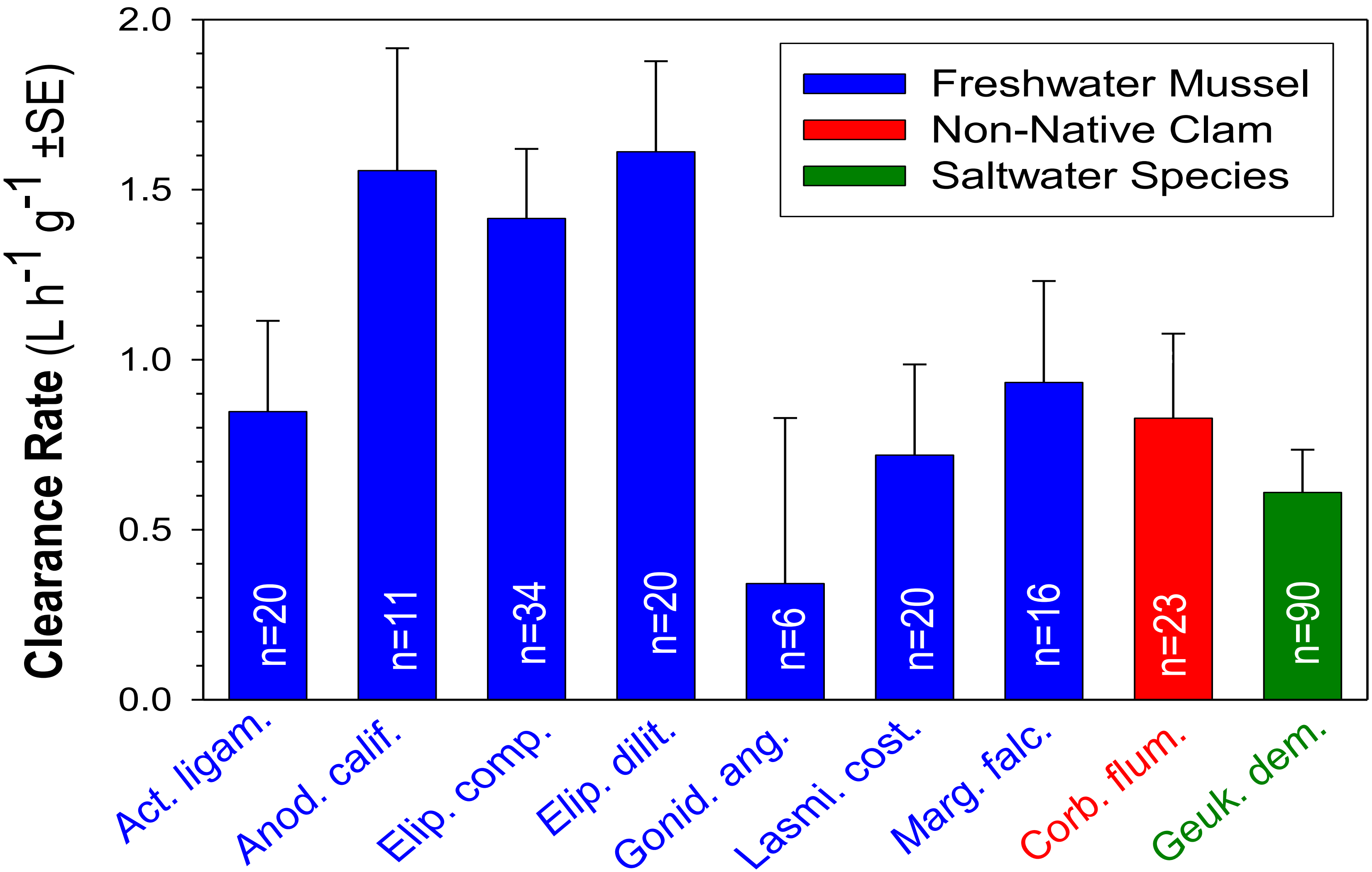
Clearance Rates – Temperatures 15 - 20ºC



7 Species: 0.3 - 1.6 L/hr/g

Clearance Rates – Temperatures >20ºC



9 Species: 0.5 - 1.6 L/hr/g

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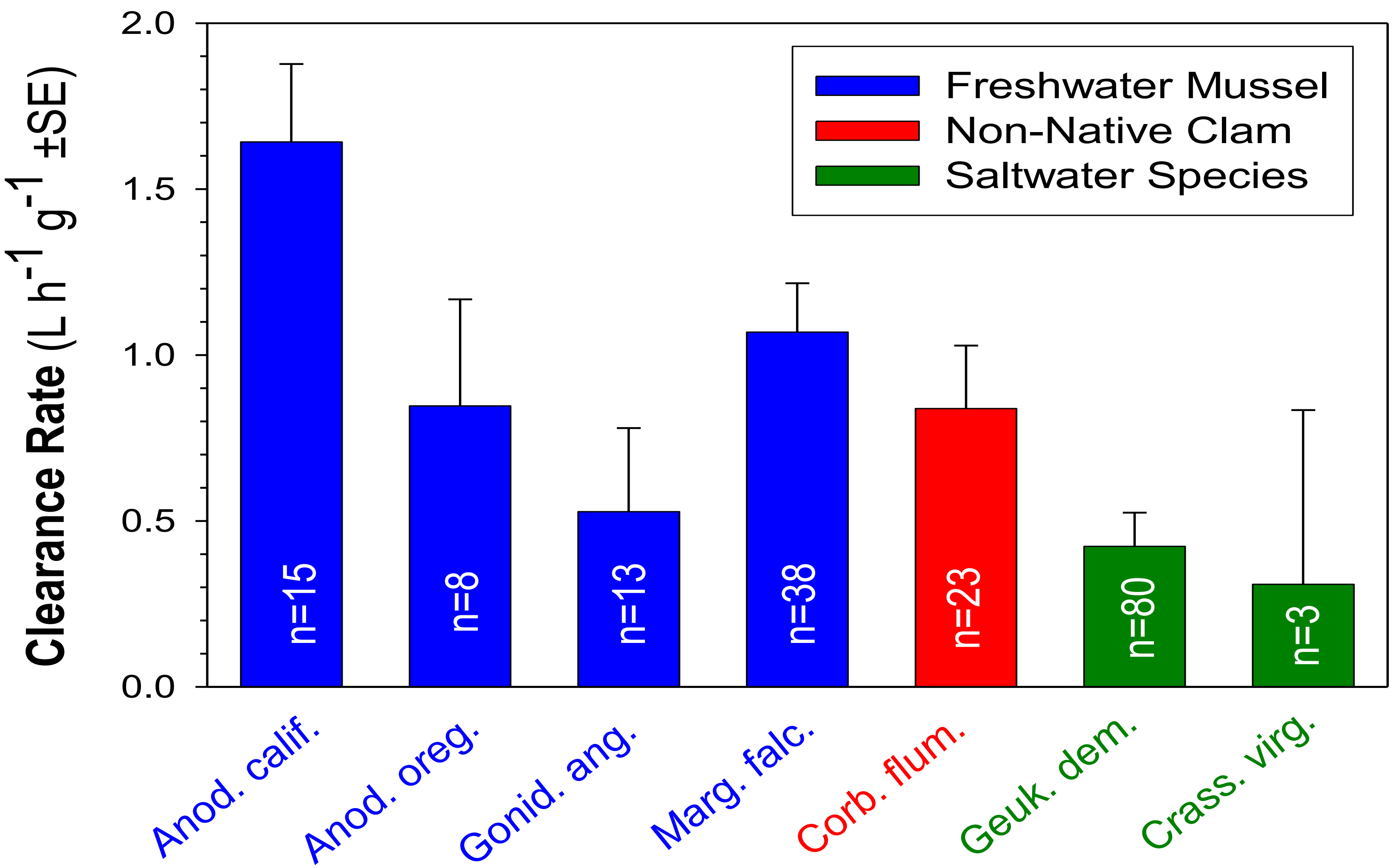
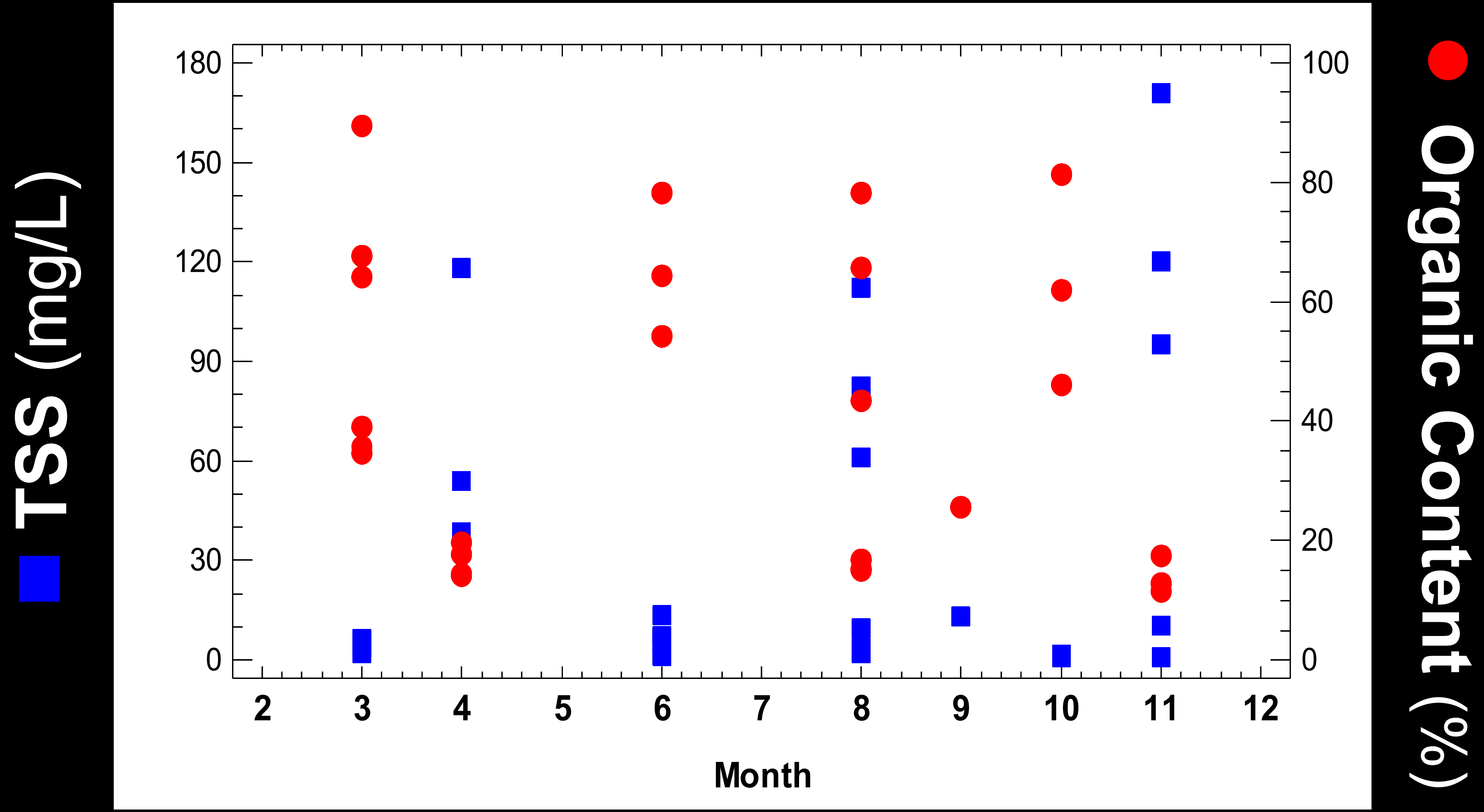
Clearance Rates – Temperatures 15 - 20ºC

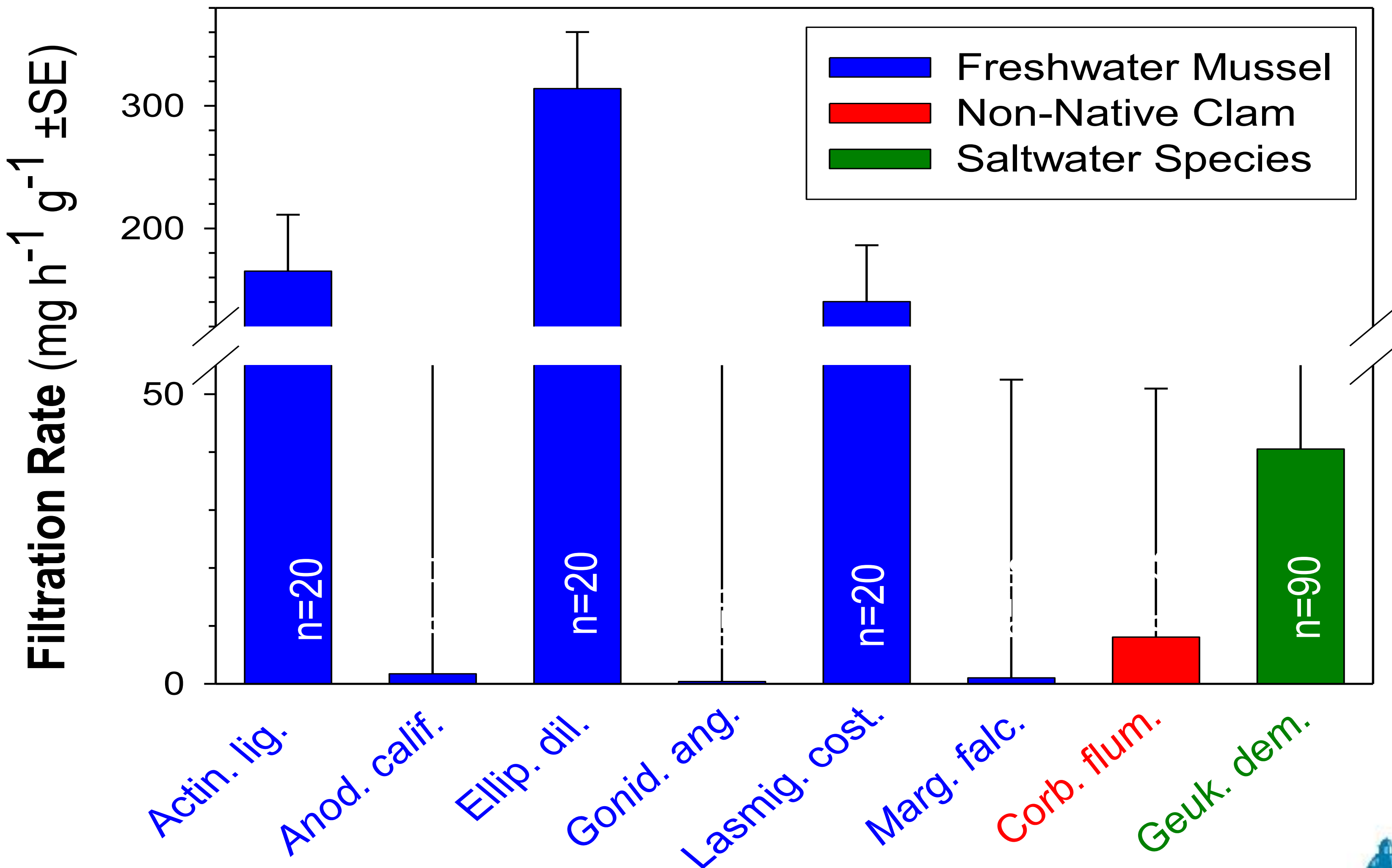


7 Species: 0.3 - 1.6 L/hr/g

Seston Composition Highly Variable

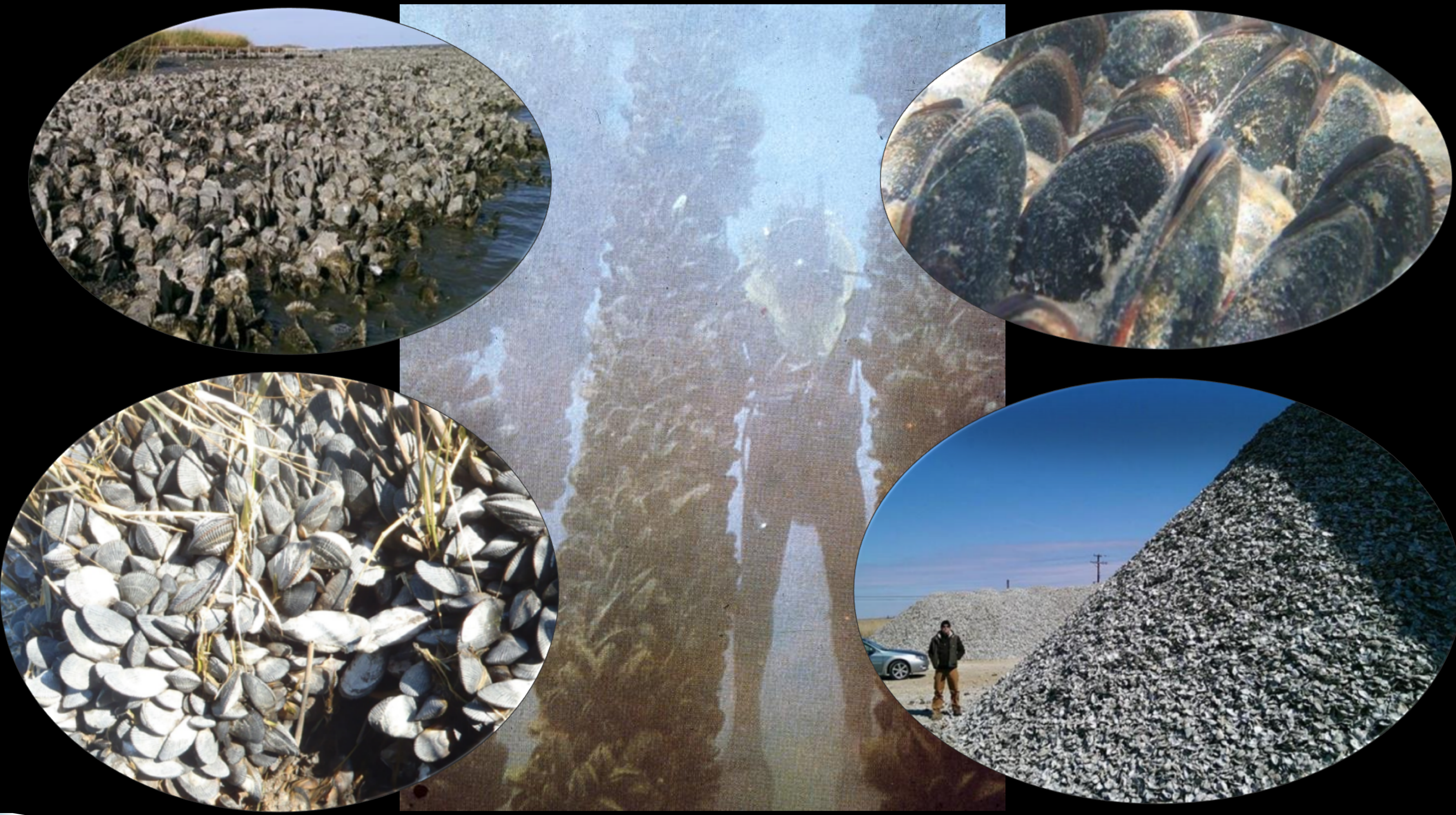


Filtration Rates – Temperatures >20ºC

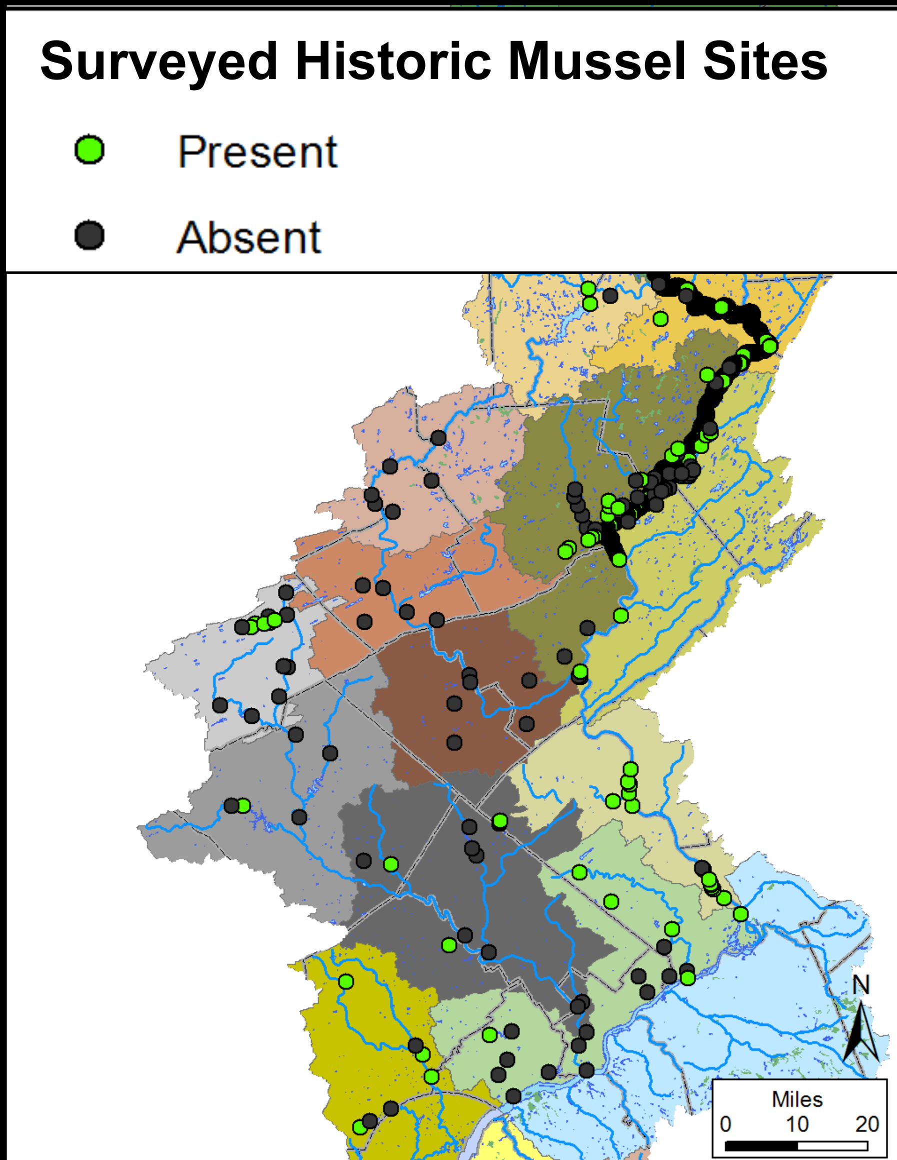


8 Species: 1 - 314 mg/hr/g

Population Biomass – Got Shellfish?



Sadly, no…. In most places



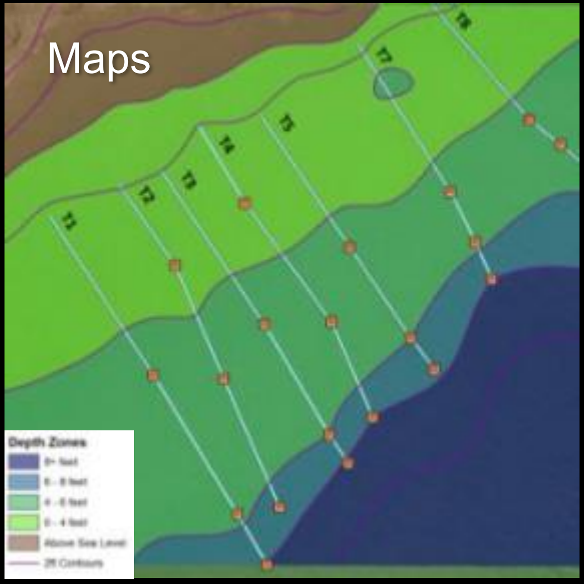
Delaware River Reference Sites

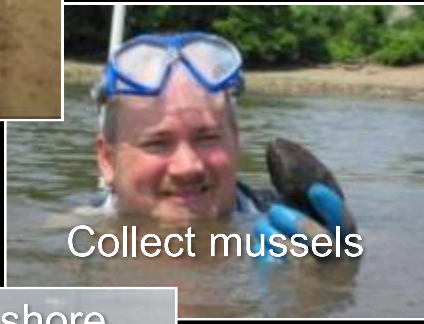
Seven Mussel Beds

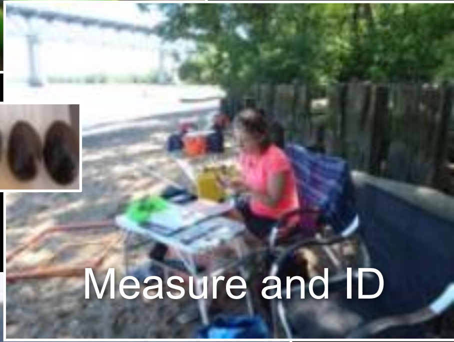
Quantitative Surveys
transects & quadrats

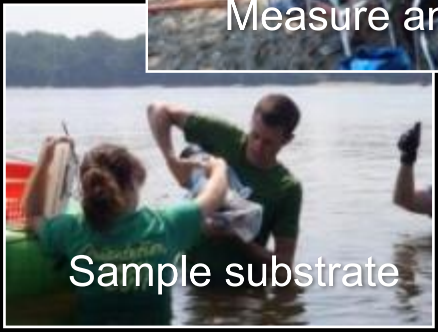
Shallow subtidal
0-8 feet below MLW

Seston, Sediments, SAV

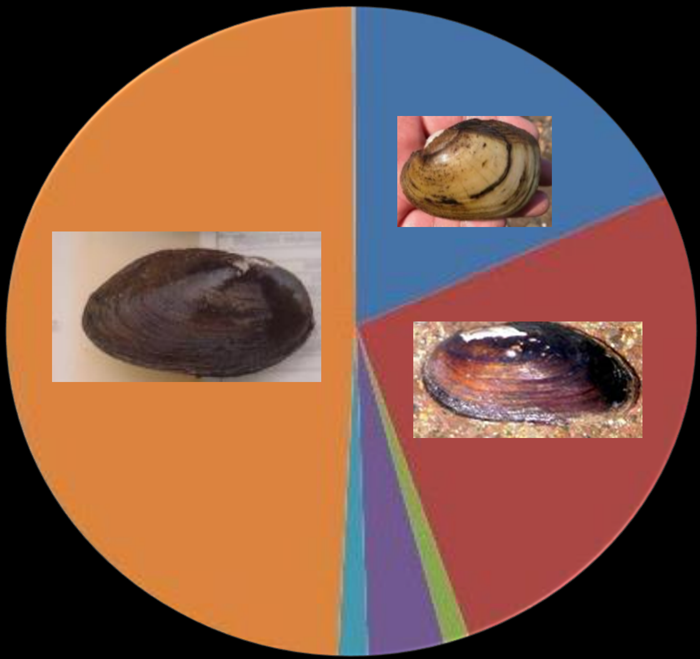




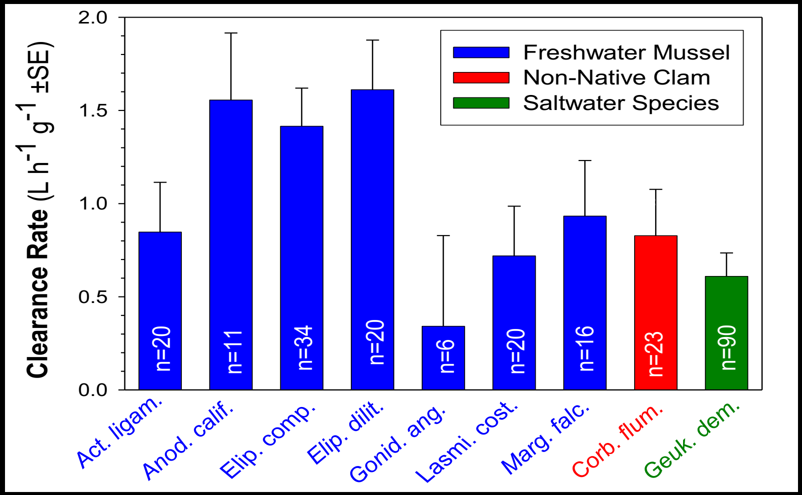




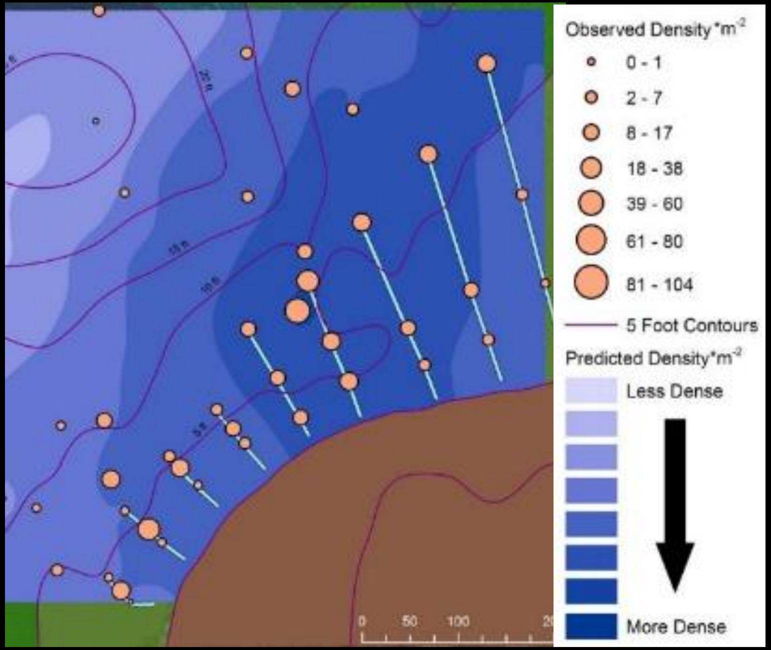
Reference Bed Data



Population Biomass by Species



Physiology Scaled to Biomass, Species, Season



Mapped Species Biomass

Water Filtration Estimates

Location	Area (m^2)	Number	Tissue Weight(g)	Clearance Rate ($L\ hr^{-1}\ g\ DTW^{-1}$)	Clearance Rate ($gal\ day^{-1}\ g\ DTW^{-1}$)	Bed Clearance Rate ($gal\ day^{-1}$)	TSS Filtration ($kg\ DW\ day^{-1}$)
Site 1	4,230	23,163	74,210	0.875	5.55	411,867	7.8
Site 2	18,648	477,389	992,074			5,506,008	104.2
Site 3	13,983	256,560	241,151			1,338,387	25.3
Site 4	35,525	1,662,570	586,163			3,253,202	61.6
Total	**72,386**	**2,419,682**	**1,893,597**			**10,509,464**	**198.9**

=10 tons dry TSS per hectare per year

Pollutant Removal

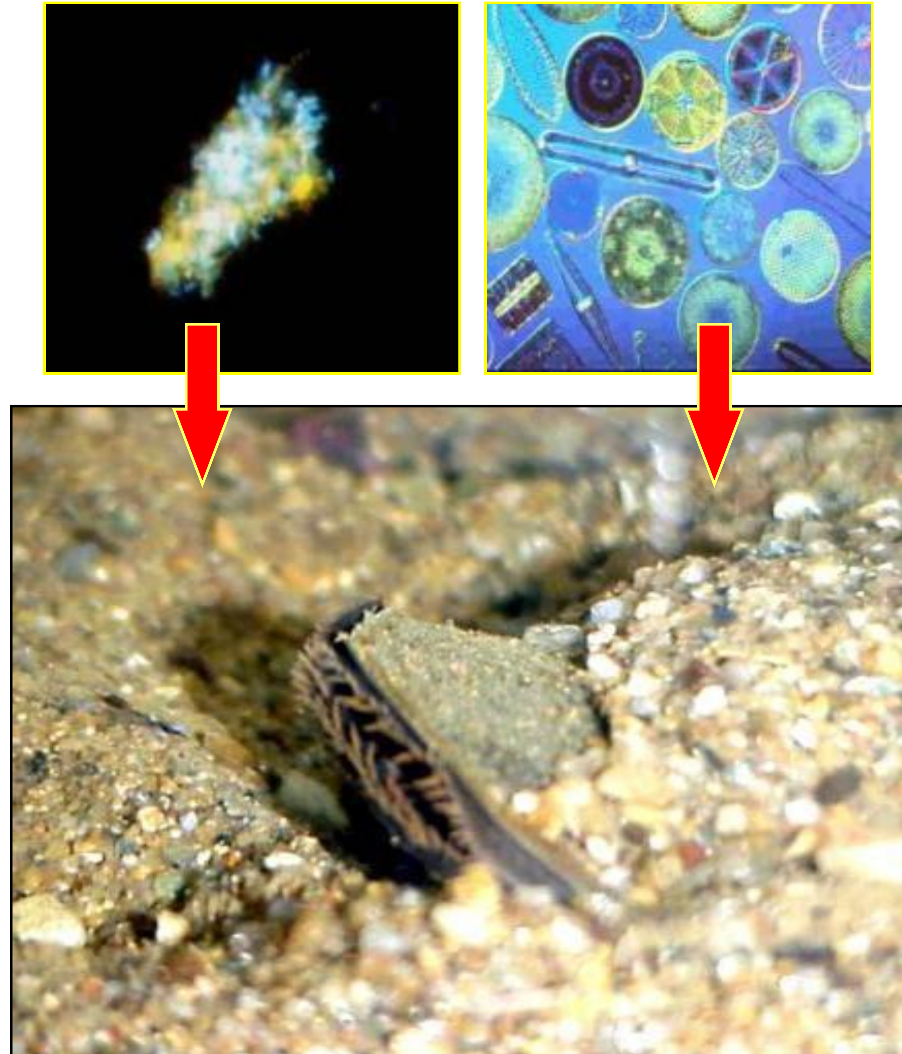
Total Suspended Solids

- 10 tons (dry) per hectare per year

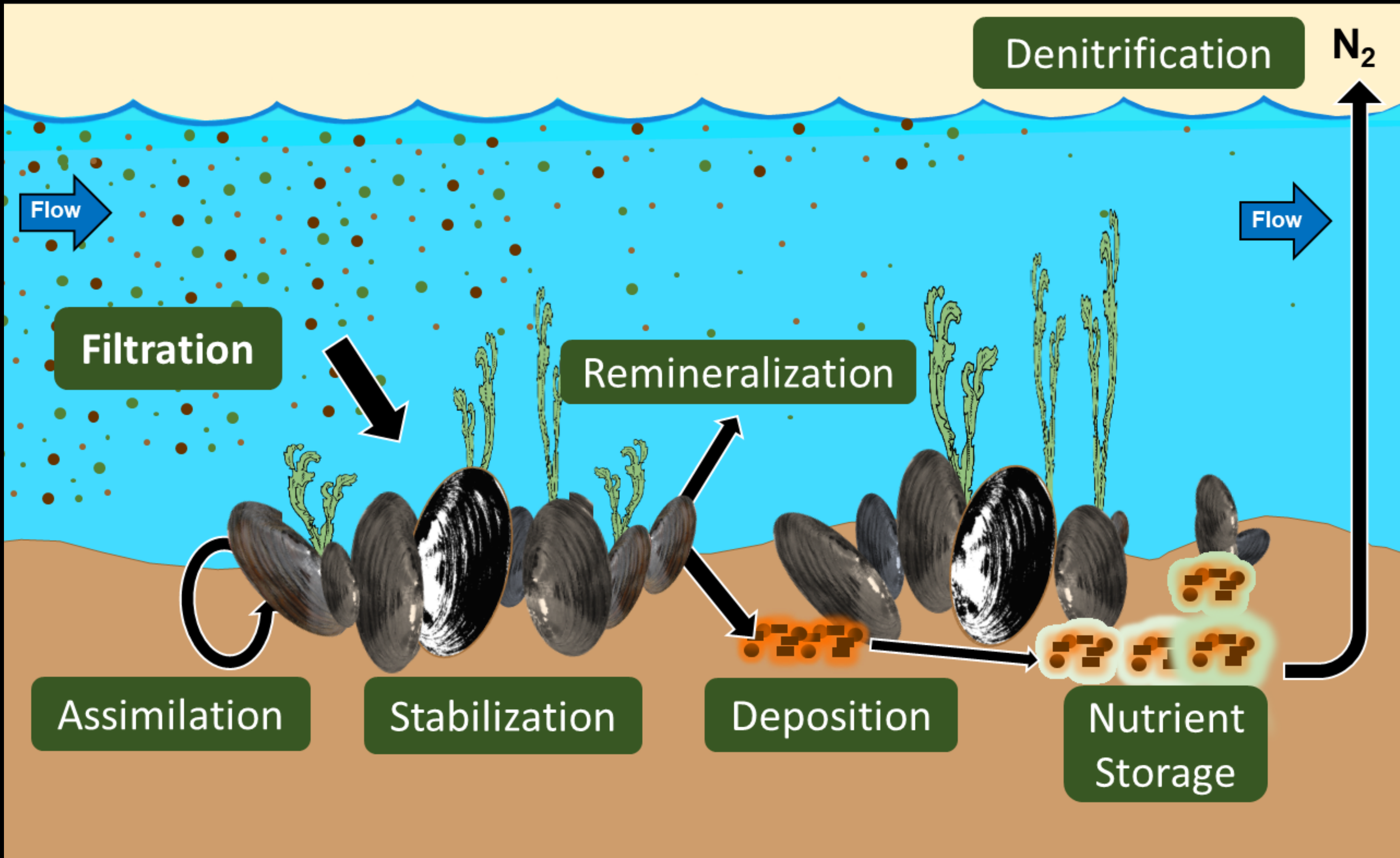
Particulate Nitrogen Removal

- 77 kg N per hectare per year (420 lbs N/acre)

They must do this to satisfy their nutritional demands

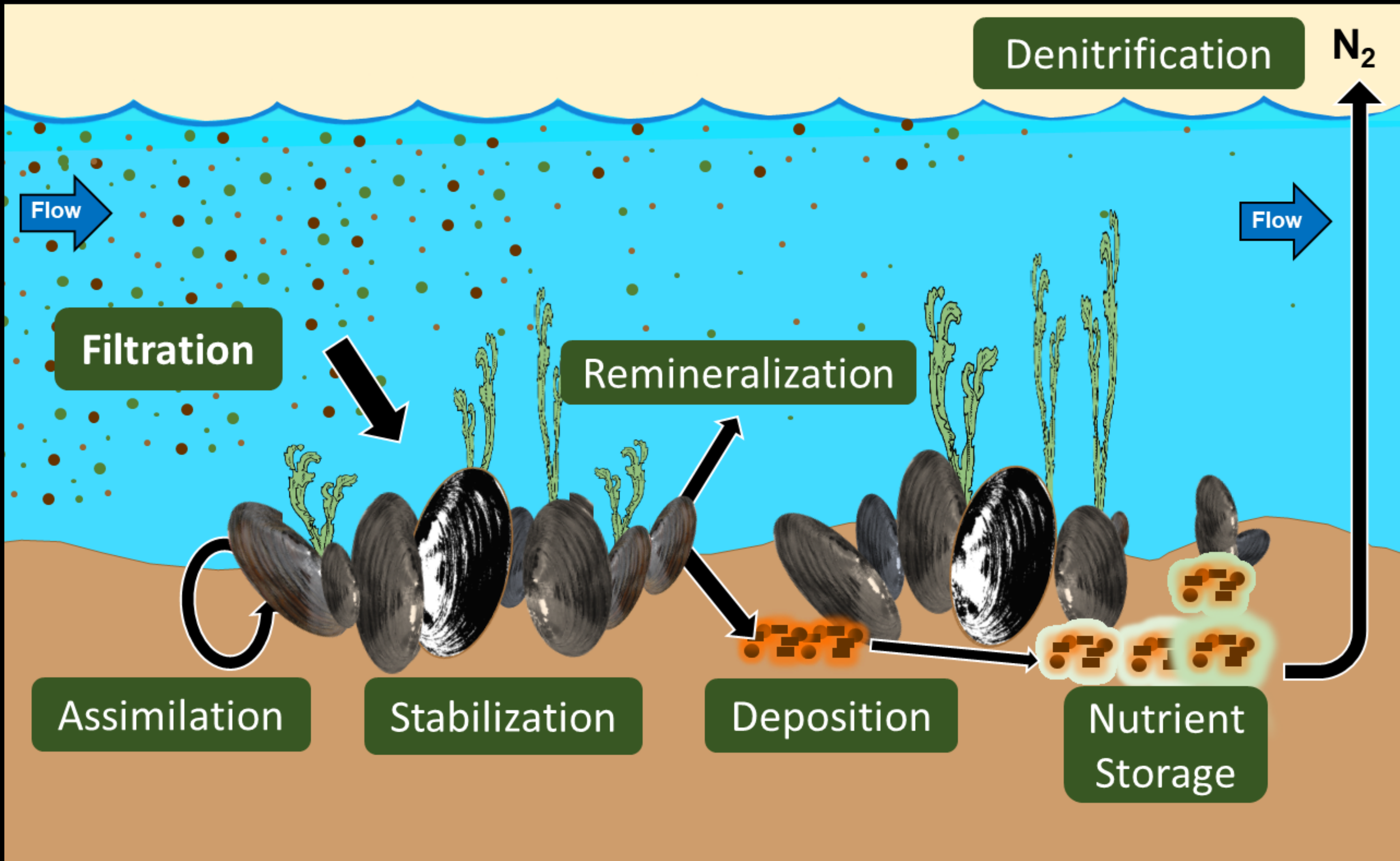


Effects of Mussel Beds



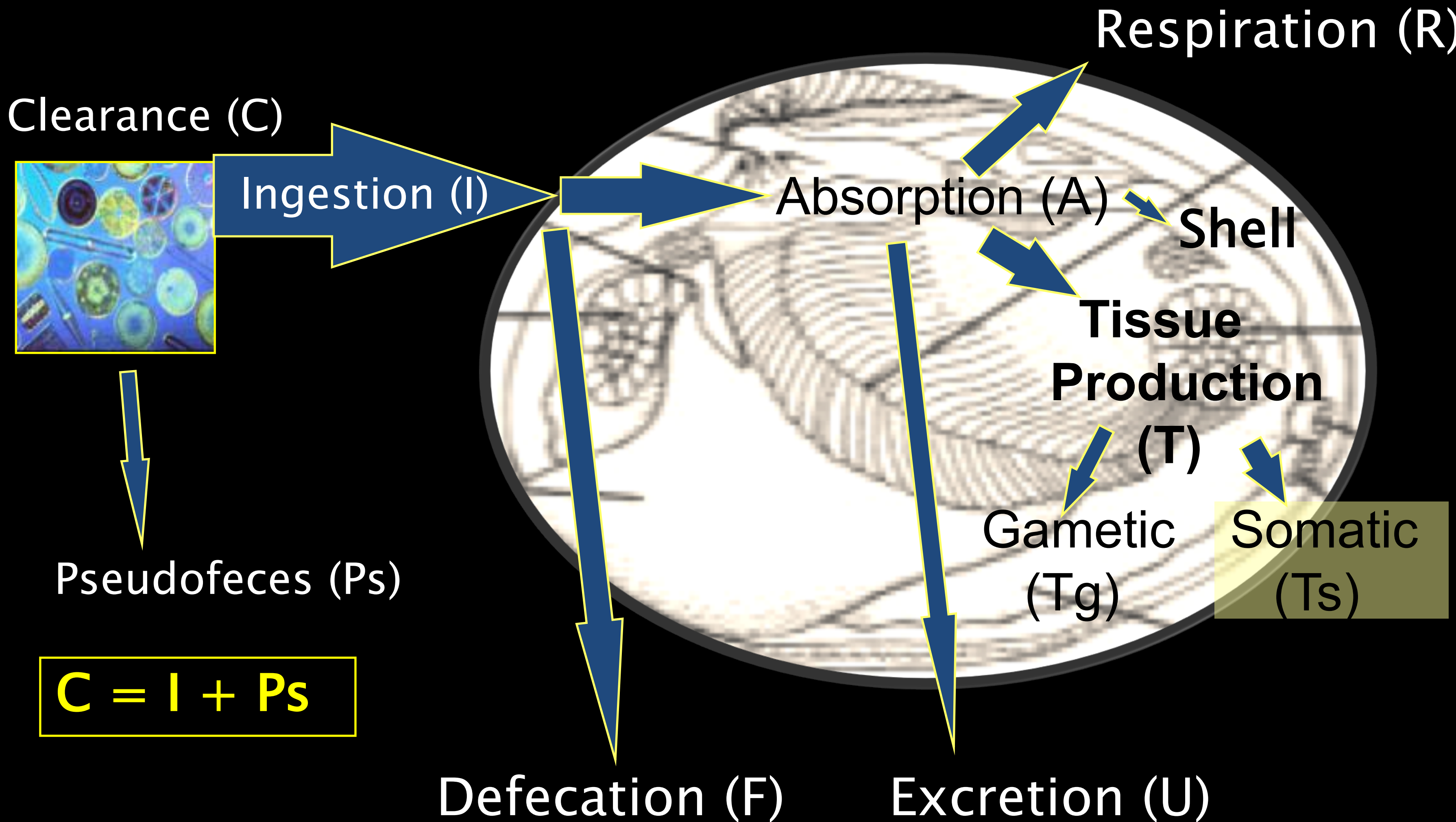
Kreeger et al. 2018. J. Shellfish Res.

But is it Really Removed?



What is the Fate of the Filtered Matter?

Fate of Filtered Seston?

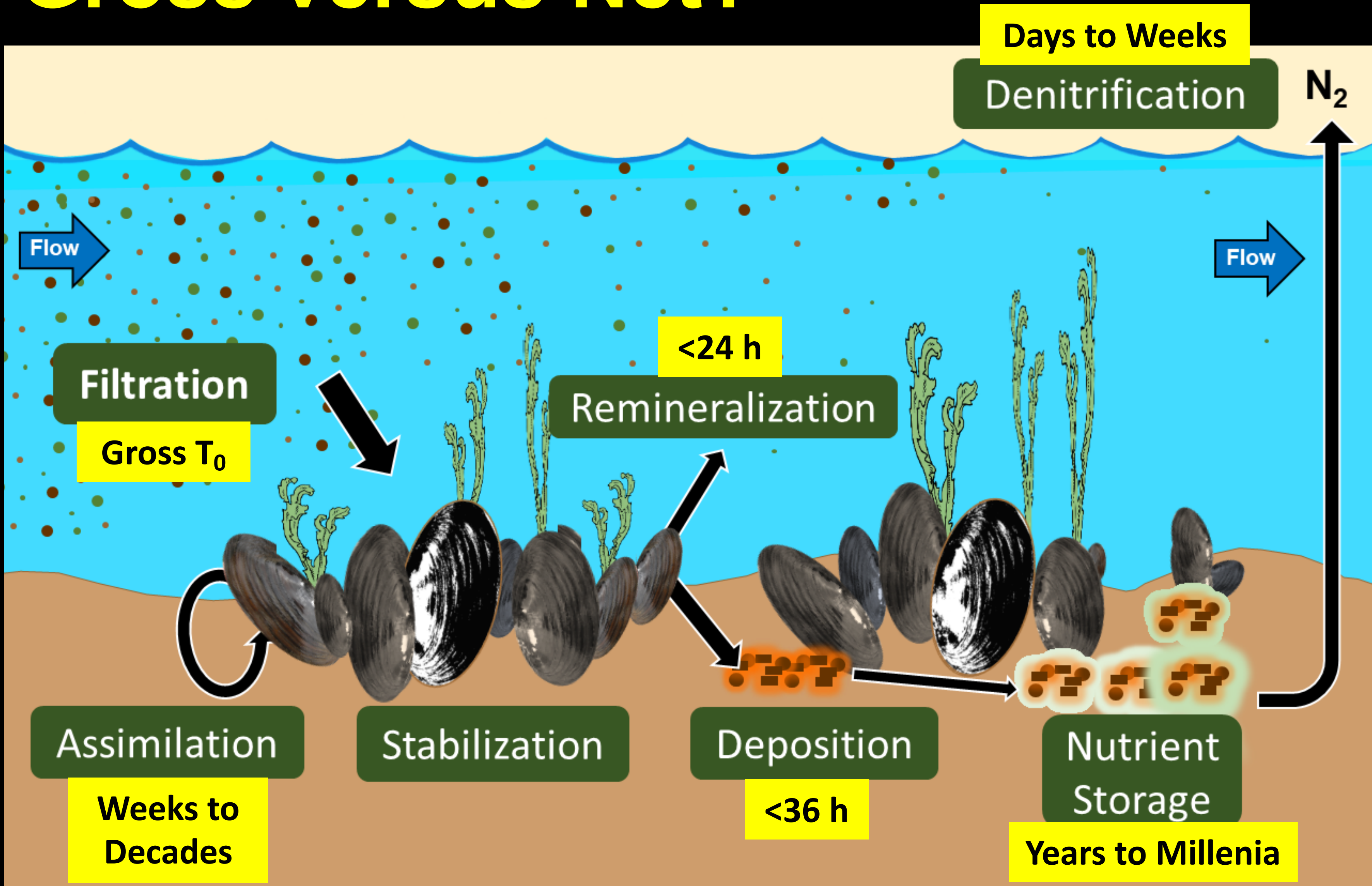


$C = I + Ps$

$I = F + U + R + T$

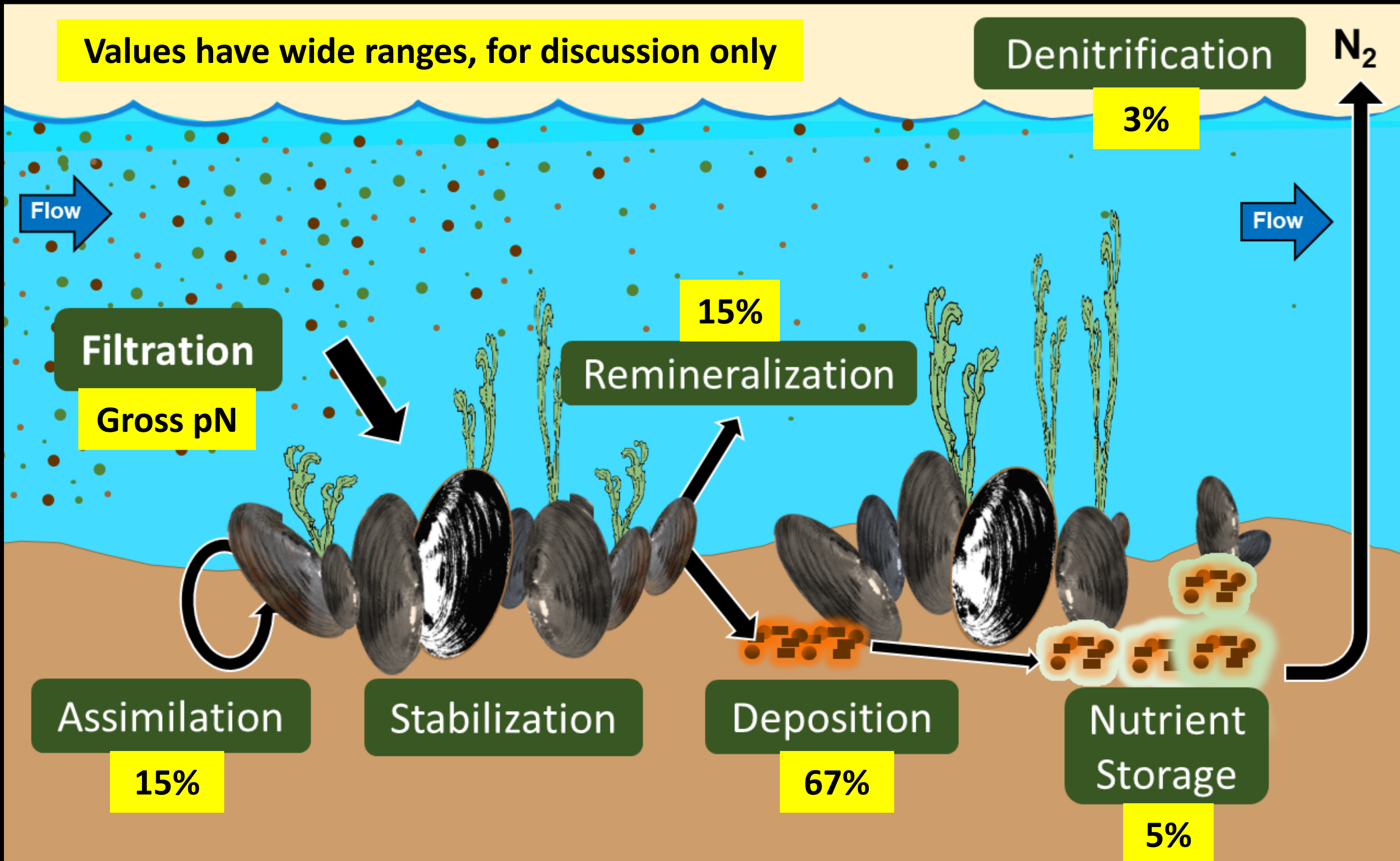
$AE = [\, U+R+T \,] \,/\, I \times 100\%$

Gross versus Net?



Rapid Recycling vs. Long-Term Sequestration

Is Net Removal Substantial?



It can be…

Even a 3% net loss per week can still be a lot of pounds N per year if the population biomass and pN availability is high

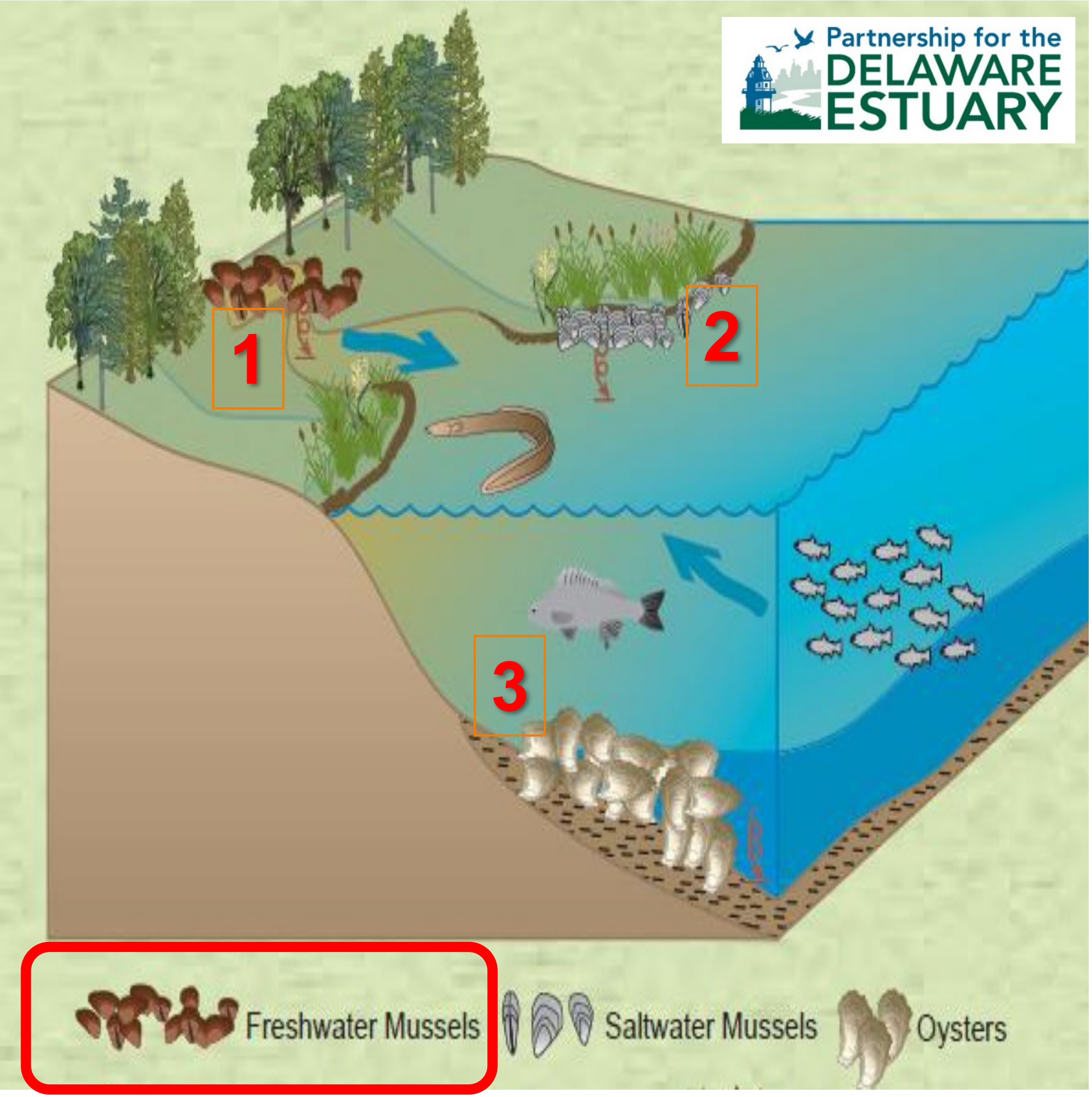
Flux

Loss of Nature's Benefits

Less Pollutant Removal

Headwaters to Ocean Shellfish Restoration

1. Non-tidal
2. Intertidal
3. Subtidal



What are the Management Options?

Goals

Biodiversity (ESA)	**Clean Water** (CWA)	**Other** (F&W, erosion control, etc.)

Targets

Strategies

Tactics

Places

What are the Management Options?

Level			
Goals	**Biodiversity** (ESA)	**Clean Water** (CWA)	**Other** (F&W, erosion control, etc.)
Targets	**Rare Species**		
Strategies	**Conservation**	**Restoration**	
Tactics	Protection	Traditional BMPs	Fish Hosts
	Habitat Improvement	Hatchery Augmentation	
Places	**Lakes & Ponds**	**Streams & Rivers**	**Tidal Shorelines**

What are the Management Options?

Goals

Clean Water
(CWA)

Targets

Mussel Beds

Strategies

Conservation

Restoration

Tactics

Protection

Traditional BMPs

Fish Hosts

Habitat Improvement

Hatchery Augmentation

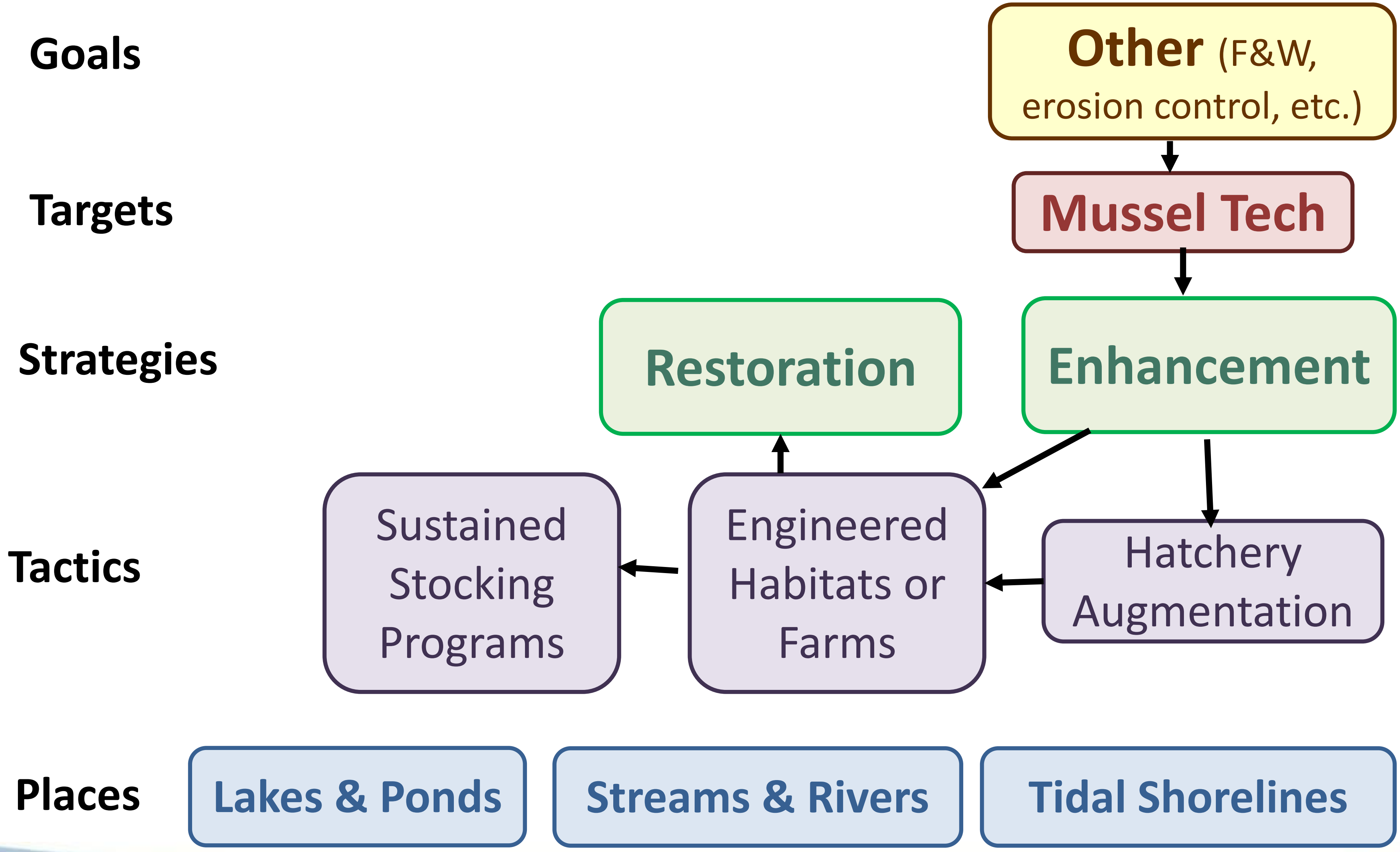
Places

Lakes & Ponds

Streams & Rivers

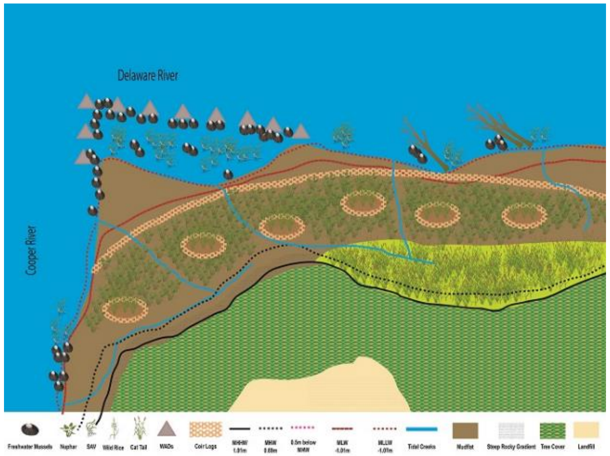
Tidal Shorelines

What are the Management Options?



Enhancement Examples

Urban Living Shorelines



Camden, NJ

Philadelphia, PA

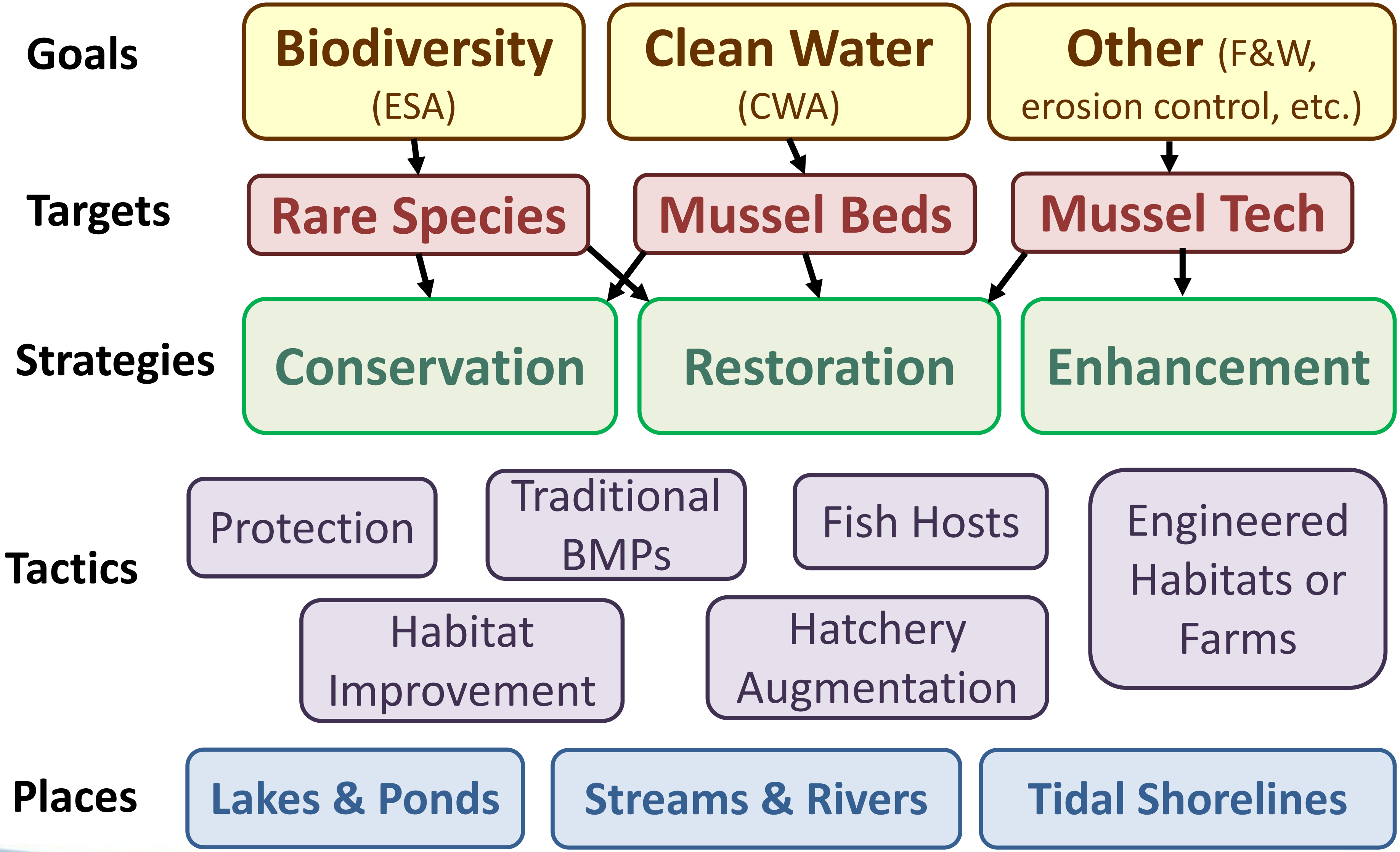
Wilmington, DE

Nutrient Bioextraction Farms

Aquaculture Systems at Impairment Sites

Rotating Crops

Lots of Management Options



Important Questions

Can Mussels be Restored (or Enhanced) Anywhere?

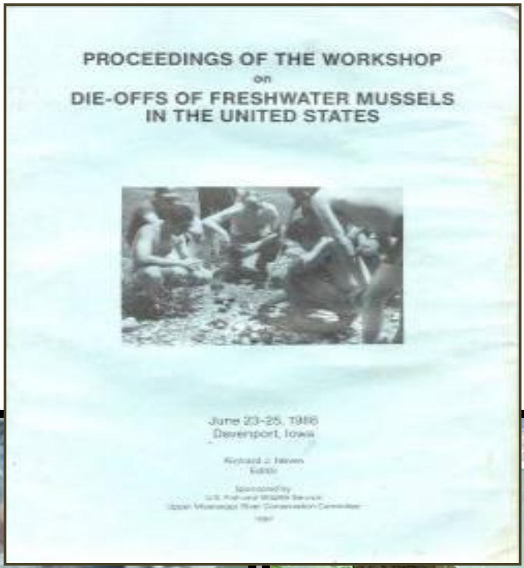
How can we Preserve Genetics?

What is the Effectiveness and ROI for Different Options?

Would a Mussel BMP be a Magic Bullet for Water Quality?

Freshwater Mussels in Decline

Biodiversity



PROCEEDINGS OF THE WORKSHOP
on
DIE-OFFS OF FRESHWATER MUSSELS
IN THE UNITED STATES

June 23-25, 1986
Davenport, Iowa

Population
Biomass

Culprits

Stormwater

Unstable Bottoms

Reduced Riparian Canopy

Loss of Fish Hosts

Dams, Habitat Degradation

Water Quality

Exotic Species

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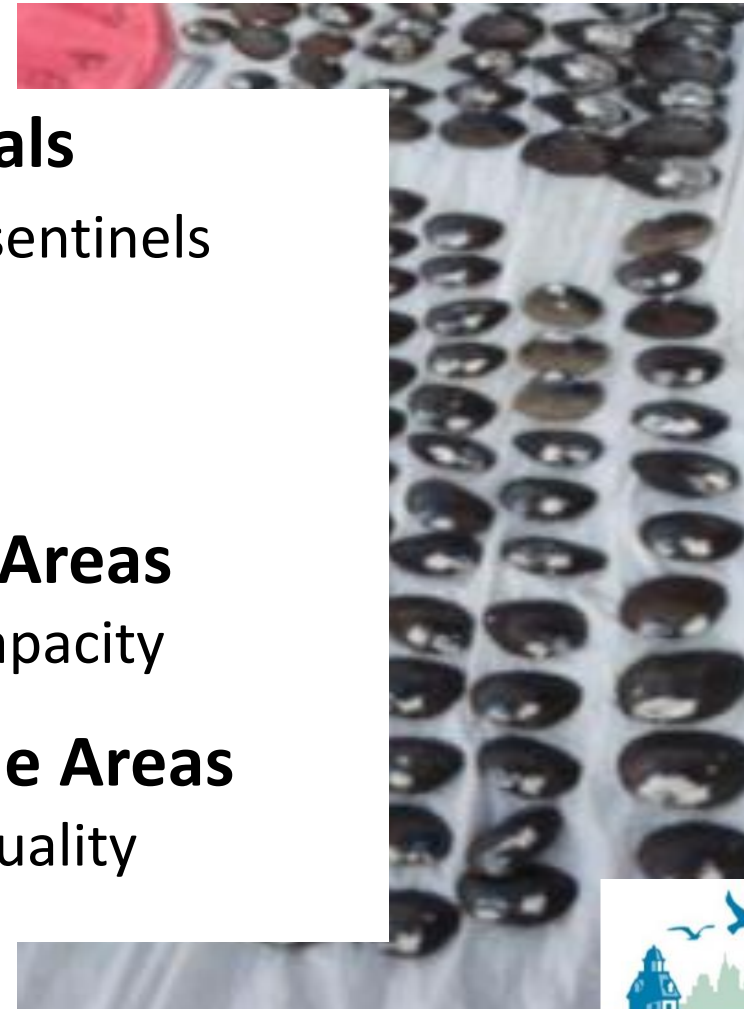
Gauge Restoration Readiness



- **Reintroduction Trials**
  - monitor tagged sentinels
- **Caging/Silo Trials**
  - monitor fitness
- **Prioritize Suitable Areas**
  - gauge carrying capacity
- **Improve Unsuitable Areas**
  - habitat and water quality

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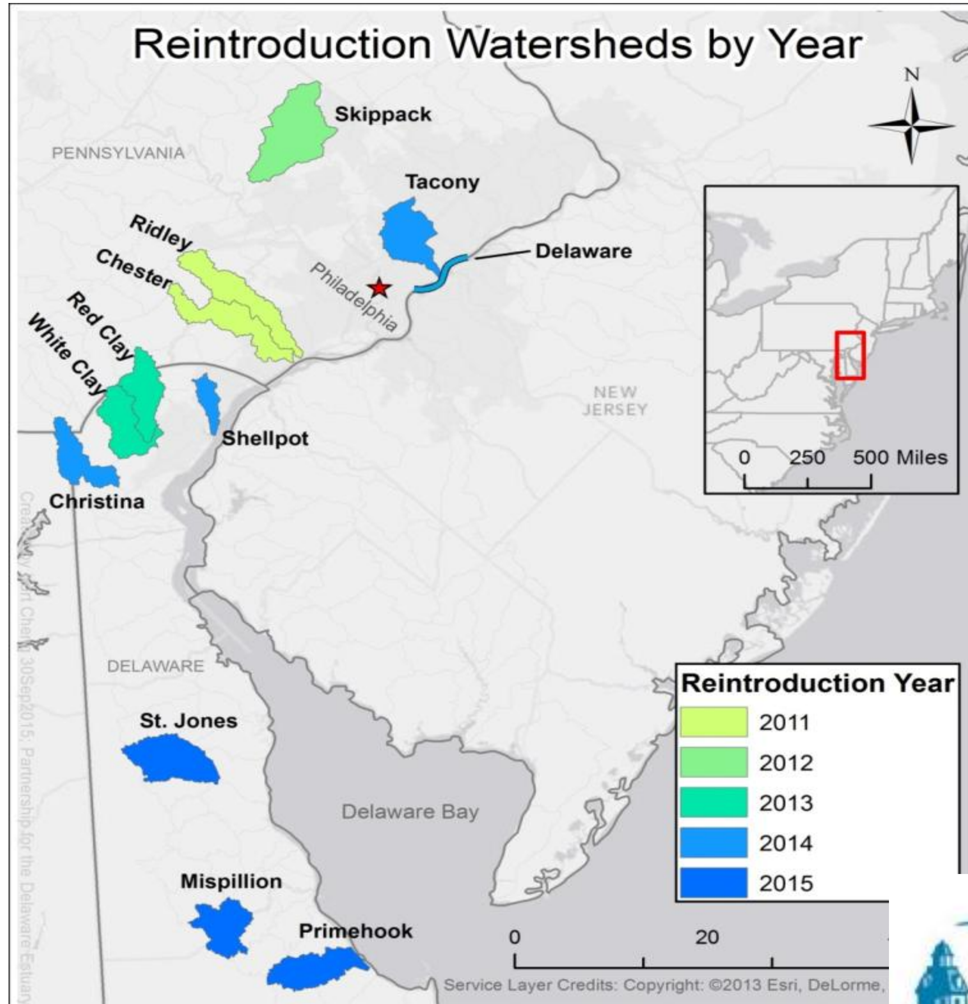
Restoration Via Reintroduction

Utterbackiana implicata

Elliptio complanata



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Juvenile Growth Comparisons

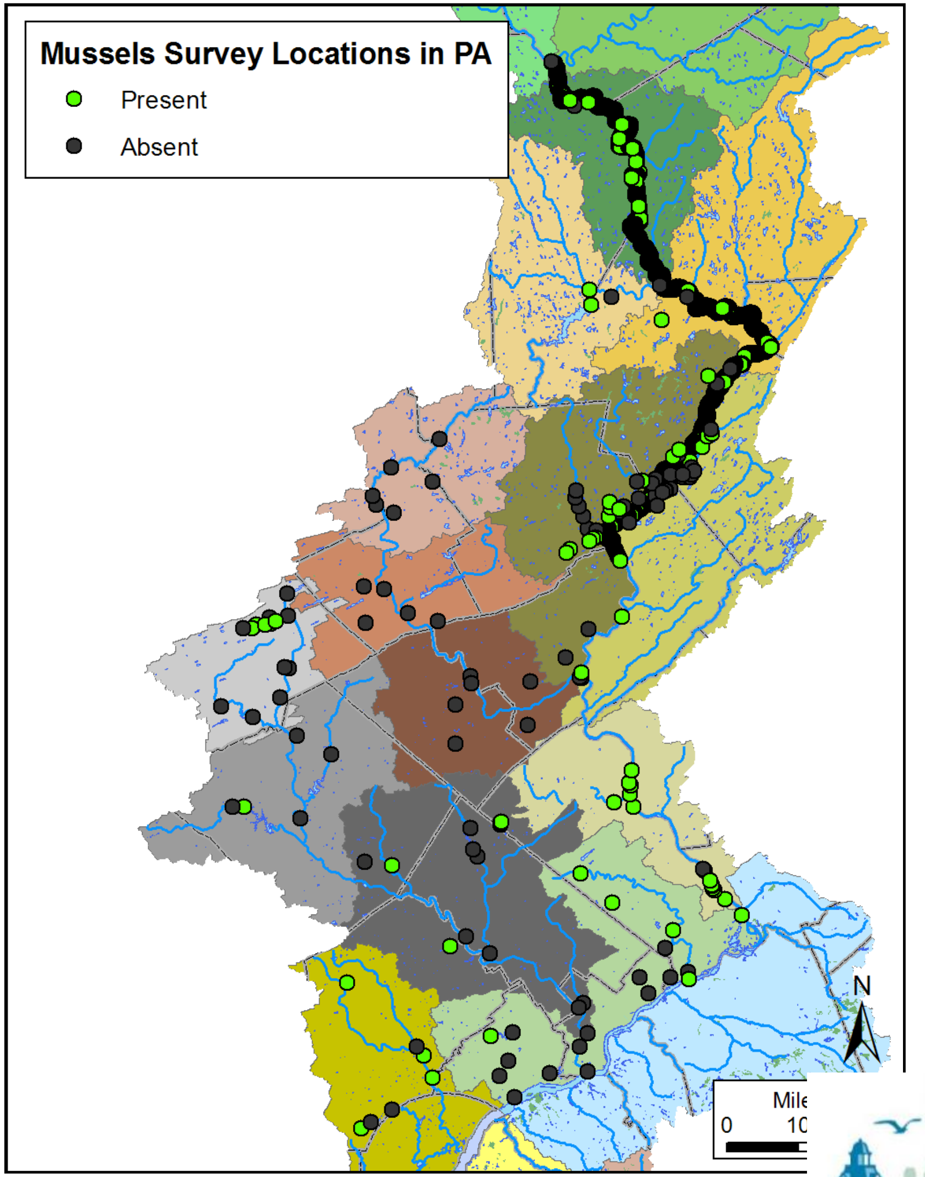
Site	Basket #	Deployed #	Start SL (mm)		End SL (mm)		Trial Days	Daily Growth (mm)	Survival (%)
			Mean ± SEM	N	Mean ± SEM	N			
Seaport Museum	1	100	32.1 ± 0.74	100	50.7 ± 1.2	43	67	0.28	43
Green Lane Reservoir	1	400	24.9 ± 0.46	100	65.8 ± 0.30	316	400	0.10	79
Green Lane Reservoir	2	400	24.7 ± 0.38	100	38.8 ± 0.47	100	231	0.06	91
Green Lane Reservoir								0.09	100
Green Lane Reservoir								0.09	99
Green Lane Reservoir								0.09	98
Green Lane Reservoir								0.09	97
Longwood-1								0.06	49
Longwood-1								0.07	55
Longwood-1								0.07	47
Longwood-2								0.08	52
Longwood-2								0.08	25
Longwood-2								0.07	33
Van Sciver Lake								0.09	
Van Sciver Lake								0.10	59
Van Sciver Lake								0.11	
Winterthur-1								0.07	87
Winterthur-1								0.06	81
Winterthur-1								nd	nd
Winterthur-2								0.06	8
Winterthur-2								0.07	32
Winterthur-2	3	1000	18.7 ± 0.30	100	35.9 ± 1.1	20	321	0.05	18

Genetics and Ecological Preservation

- **Genetics Management Plan**
  - understand genetic variation in target species
  - use appropriate broodstock sources for specific watersheds and sub-watersheds
  - hatchery methods to minimize selection, drift
  - monitor and compare genetics in restoration populations to natal genetics
- **Restore/Enhance Native Species Assemblages**
  - avoid species or gene swamping
  - target mixed species in natural abundances/sizes

Low Fruit

- 95% of streams in southeast PA have no mussels left
- 1000's of places for living shorelines
- Focus initial projects in areas where the need is greatest and the risks minimal
- In parallel, fill data gaps



Effectiveness?   3 Case Studies

Alewife floaters

Anodonta implicata

Ribbed mussels

Geukensia demissa

Oysters

Crassostrea virginica

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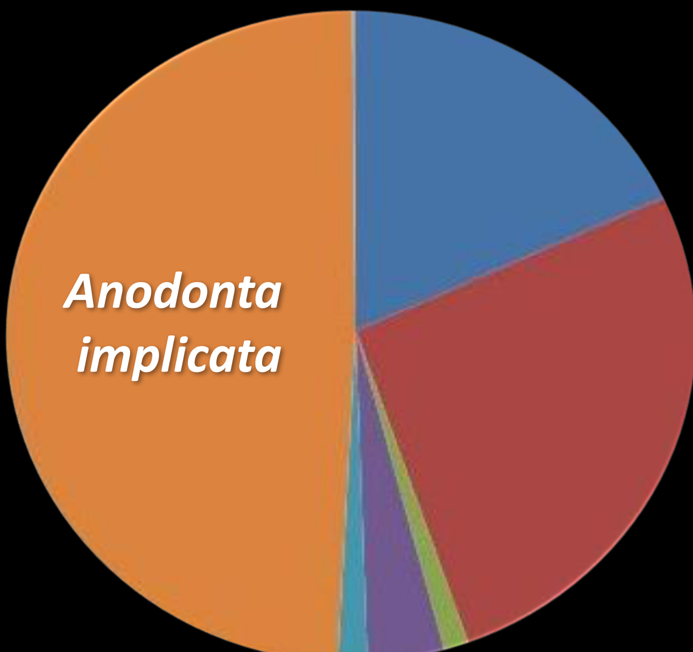
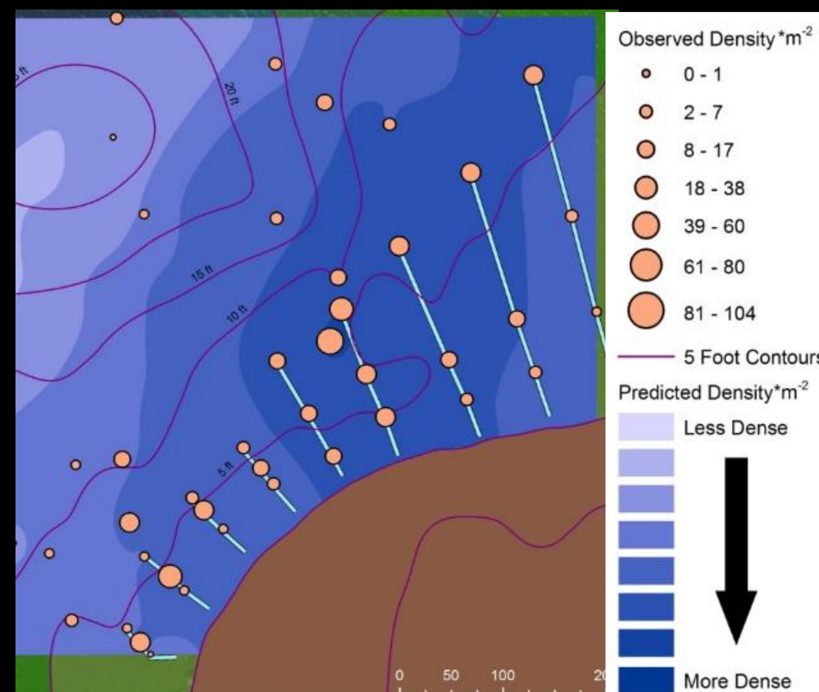
Alewife Floaters

A functional co-dominant in tidal Delaware River

Population Biomass by Species



Densities up to 100 per square meter



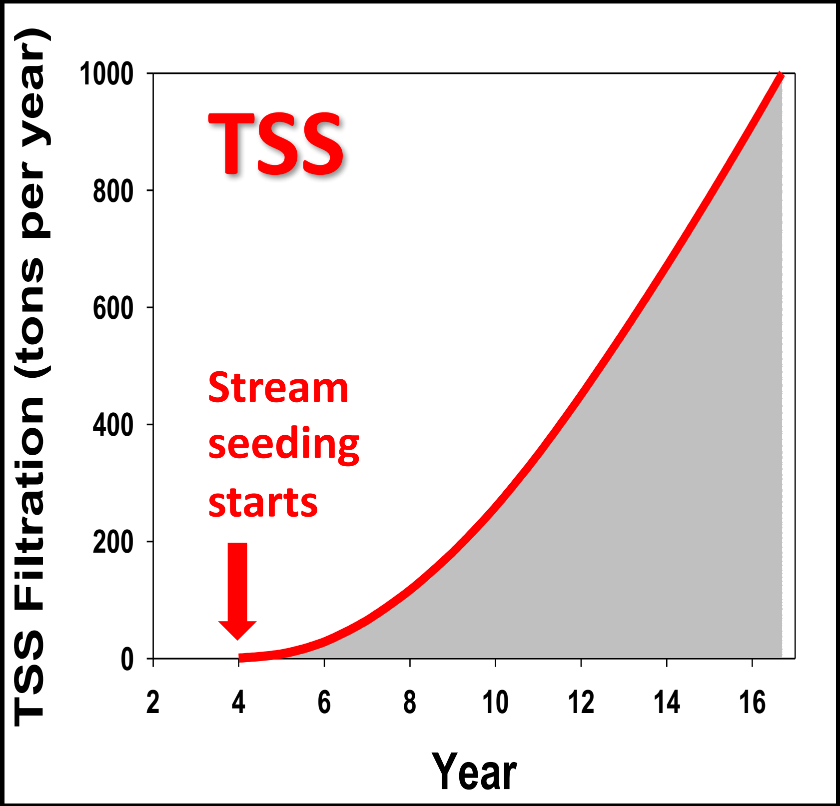
Alewife Floaters

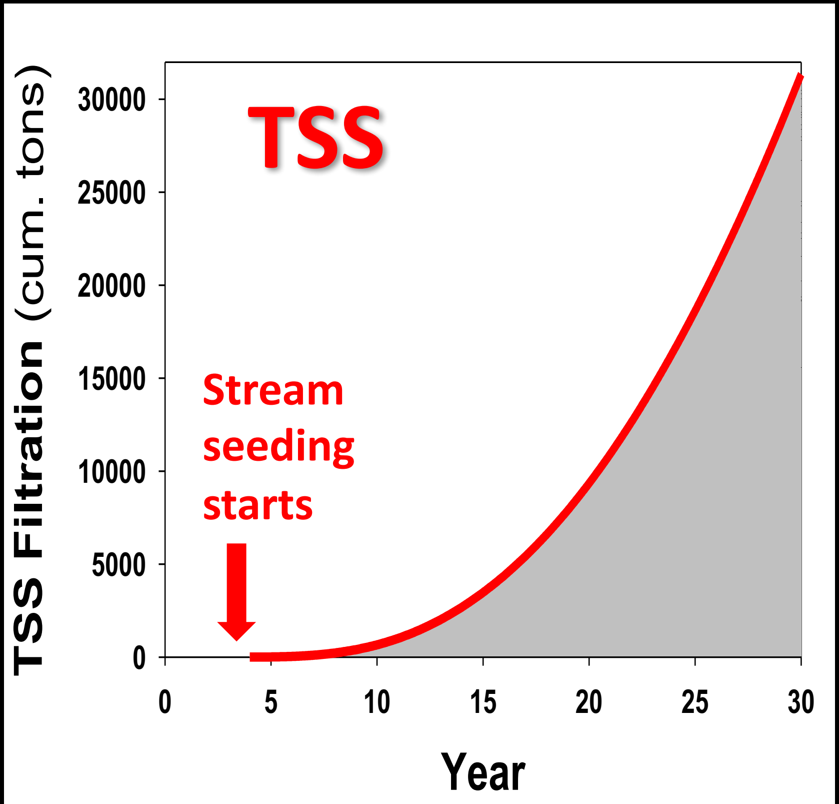
Investment in Mussel Hatchery

- Produce 500,000 seed per year
- Seed are stocked into impaired streams
- Survival ~90%, lifespan ~30 years, normal growth
- Costs $400,000 per year

Alewife Floaters

Predicted Outcomes: Seston Filtration



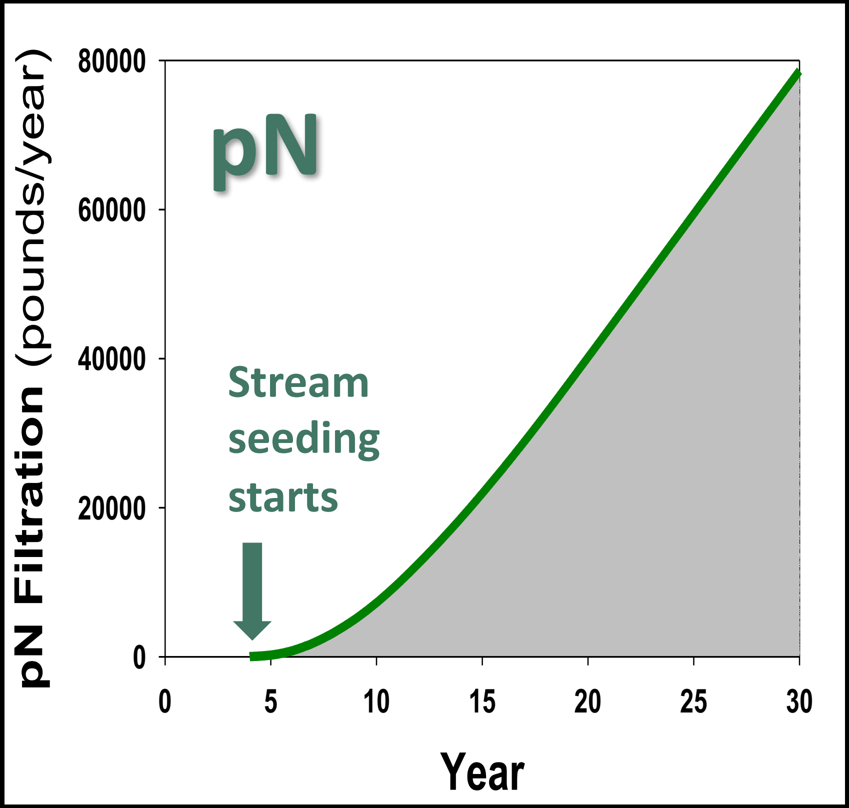


~1,000 tons per year by Yr 16

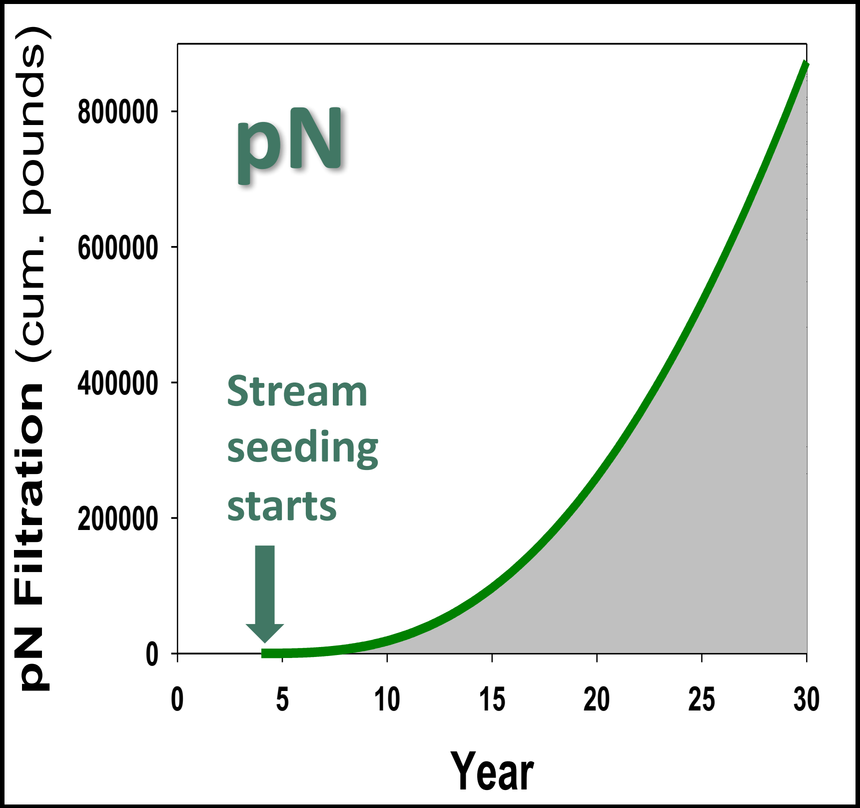
>30,000 tons TSS by Yr 30

Alewife Floaters

Predicted Outcomes: Nitrogen Filtration



~78,000 lbs/yr by Year 30



>870,000 total lbs by Year 30

Alewife Floaters

Return on Investment ?

- **Healthy mussel bed ~420 pounds N per acre/yr**
- **TSS removal would cost $400 per ton** (dry weight)
- **Nitrogen removal would cost $15 per pound**

ROI analyses ignore other ecological benefits

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Ribbed Mussels

A functional dominant of salt marshes

Mussel tissue biomass exceeds 200 kg per hectare

Concentrated along edge

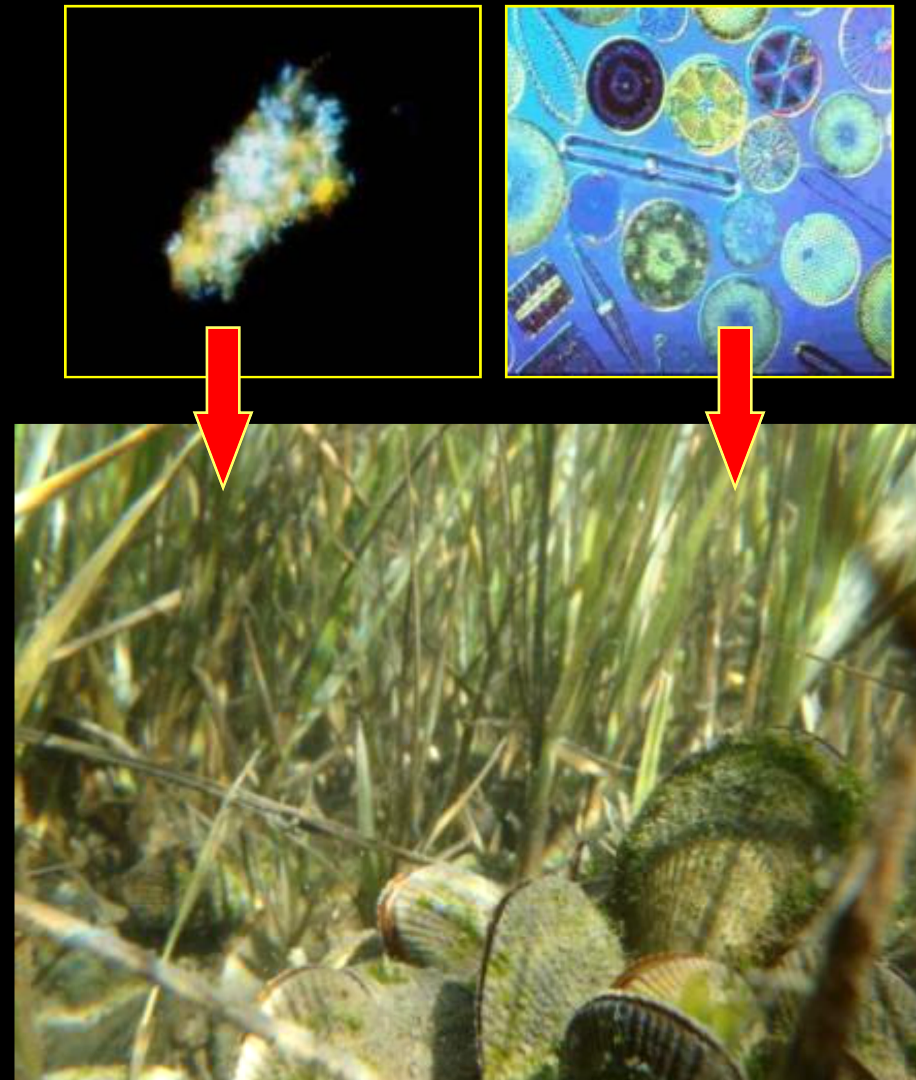
Ribbed Mussels

TSS Removal

- 92.6 metric tons per hectare per year

Particulate Nitrogen Removal

- > 1,000 lbs N per hectare per year



Moody et al. In Prep.

Ribbed Mussels

Marsh loss in Delaware Estuary

Losing:

69,518 mussels per day

8.4 mil L/d filtration capacity

Living Shorelines with Ribbed Mussels

ROI?

- Healthy mussel bed >1,000 pounds N per ha/yr
- Typical shellfish-based living shorelines cost $20-200 per linear foot (assume $100/ft)
- N services cost **$31 per pound N**

Many Other Considerations

Alewife floaters
Anodonta implicata

Pro	Con
• Effective • Opportunity • Intercept pollutants	• Carrying capacity? • Low interest • Hatchery capacity

Ribbed mussels
Geukensia demissa

Pro	Con
• Effective • Opportunity • Dual benefits • Filter bacteria	• Low interest • hatchery investment

Oysters
Crassostrea virginica

Pro	Con
• Effective • Opportunity • Industry support	• Dermo • Policy bans • Industry conflicts

LS Water Quality Benefits Comparison

Mispillion, DE (2014-current)

Hybrid Attenuating, Rural Intertidal Salt Marsh Edge

Phoenix Park, NJ (planned)

Bio-Based FW Tidal, Urban Shallow Subtidal Edge

LS Water Quality Benefits Comparison

Living Shoreline Type	Habitat	Project Area (m^2)	Species	Baseline Biomass Density g DTW /m^2	Reference Site Biomass Density g DTW/m^2	Project Goal Biomass Density g DTW/m^2	Material + Labor Cost $	Seeding Cost $	Final Pop'n Biomass Kg DTW
$75K Hybrid-Attenuating	Intertidal Salt Marsh Edge	200	Eastern oysters	5	200	150	$75,000	$0	30
			Ribbed Mussels	2	200	150		$0	30
$75K Bio-Based	Shallow Subtidal FW Tidal Edge	1000	Alewife Floaters	0.1	25	20	$50,000	$15,000	20
			Eastern Pond-mussels	0.005	4	3		$5,000	3

LS Water Quality Benefits Comparison

Living Shoreline Type	Habitat	Project Area (m^2)	Species	Animal Clearance Rate L/hr/g (seasonal mean)	Final Pop'n Clearance Rate L/hr	Seston TSS mg/L	Seston pN mg/L	Final Annual TSS Removal Kg	Final Annual pN Removal kg
$75K Hybrid-Attenuating	Intertidal Salt Marsh Edge	200	Eastern oysters	1.1	33,000	60	1.7	17,345	491
			Ribbed Mussels	0.9	27,000	60	1.7	14,191	402
$75K Bio-Based	Shallow Subtidal FW Tidal Edge	1000	Alewife Floaters	1.4	28,000	30	2.0	7,358	491
			Eastern Pond-mussels	1.2	3,600	30	2.0	946	63

LS Water Quality Benefits Comparison

Living Shoreline Type	Habitat	Project Area (m^2)	Species	% Uplift	Cost per kg N Removed	Cost per lb N Removed	Context
$75K Hybrid-Attenuating	Intertidal Salt Marsh Edge	200	Eastern oysters Ribbed Mussels	43X	$83.94	**$38.08**	Rural
$75K Bio-Based	Shallow Subtidal FW Tidal Edge	1000	Alewife Floaters Eastern Pond-mussels	219X	$135.47	**$61.47**	Urban

Mussel BMP a Magic Bullet?

Sustain and enhance traditional BMP's

- Many areas are still unsuitable for mussels
- Many areas are marginal with low mussel carrying capacity
- Continue to address root issues

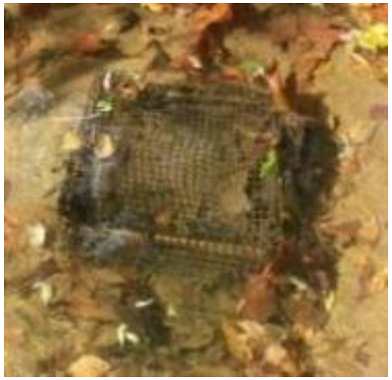
The protection, restoration and/or enhancement of mussel beds represents a plausible **addition to the BMP toolkit**

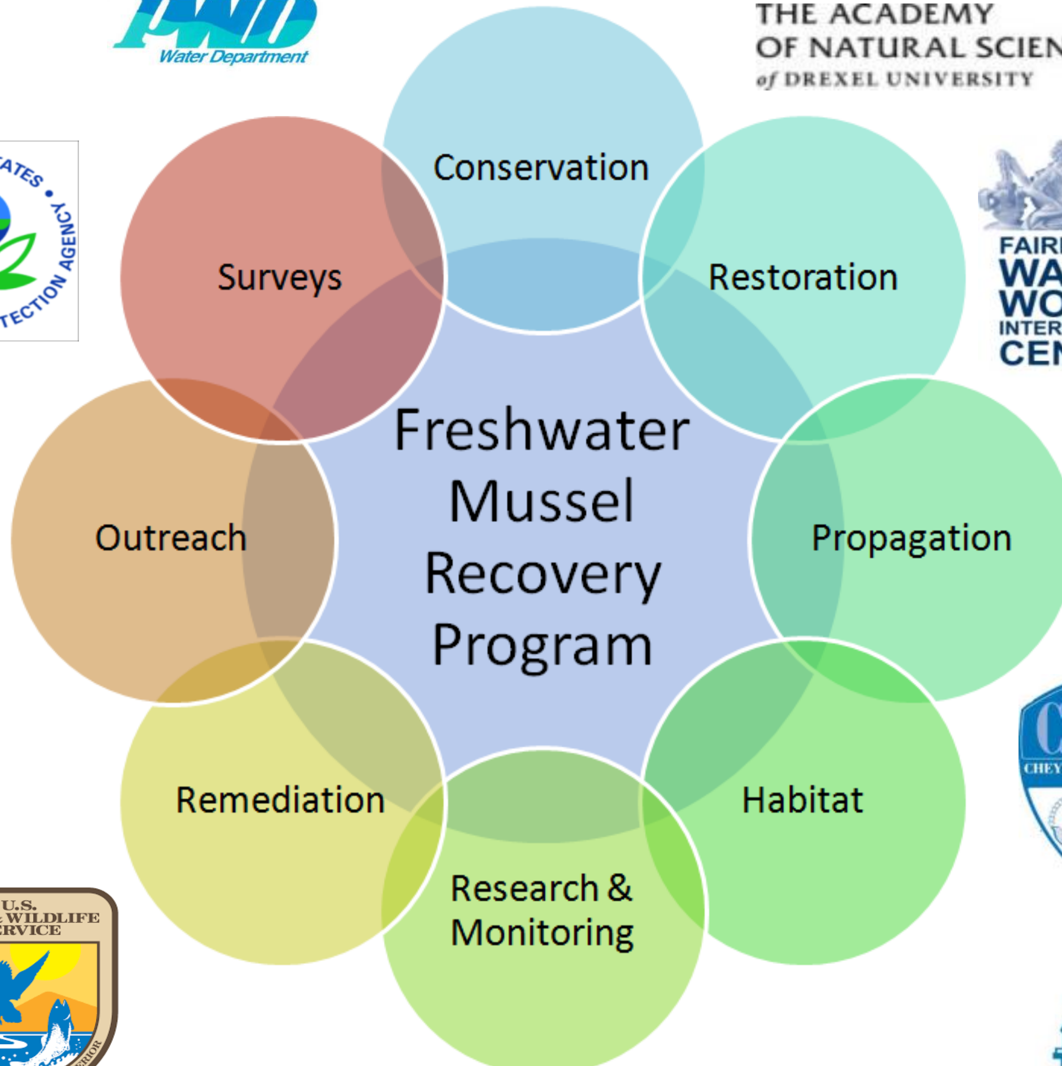
A **holistic** native shellfish BMP would diversify niches for projects, helping to intercept pollutants closer to sources

Consider climate change and future sustainability
– some mussel species are better adapted for warmth

Healthy Bivalves = Healthy Watersheds

Freshwater Mussel Recovery Program (FMRP)





Philadelphia Water Department

THE ACADEMY OF NATURAL SCIENCES of DREXEL UNIVERSITY

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY

FAIRMOUNT WATER WORKS INTERPRETIVE CENTER

CHEYNEY UNIVERSITY OF PENNSYLVANIA 1837

U.S. FISH & WILDLIFE SERVICE DEPARTMENT OF THE INTERIOR

Partnership for the DELAWARE ESTUARY

Mussel Outreach: Clean Water Benefits

River Fest

Philly and Camden, 9/7/19

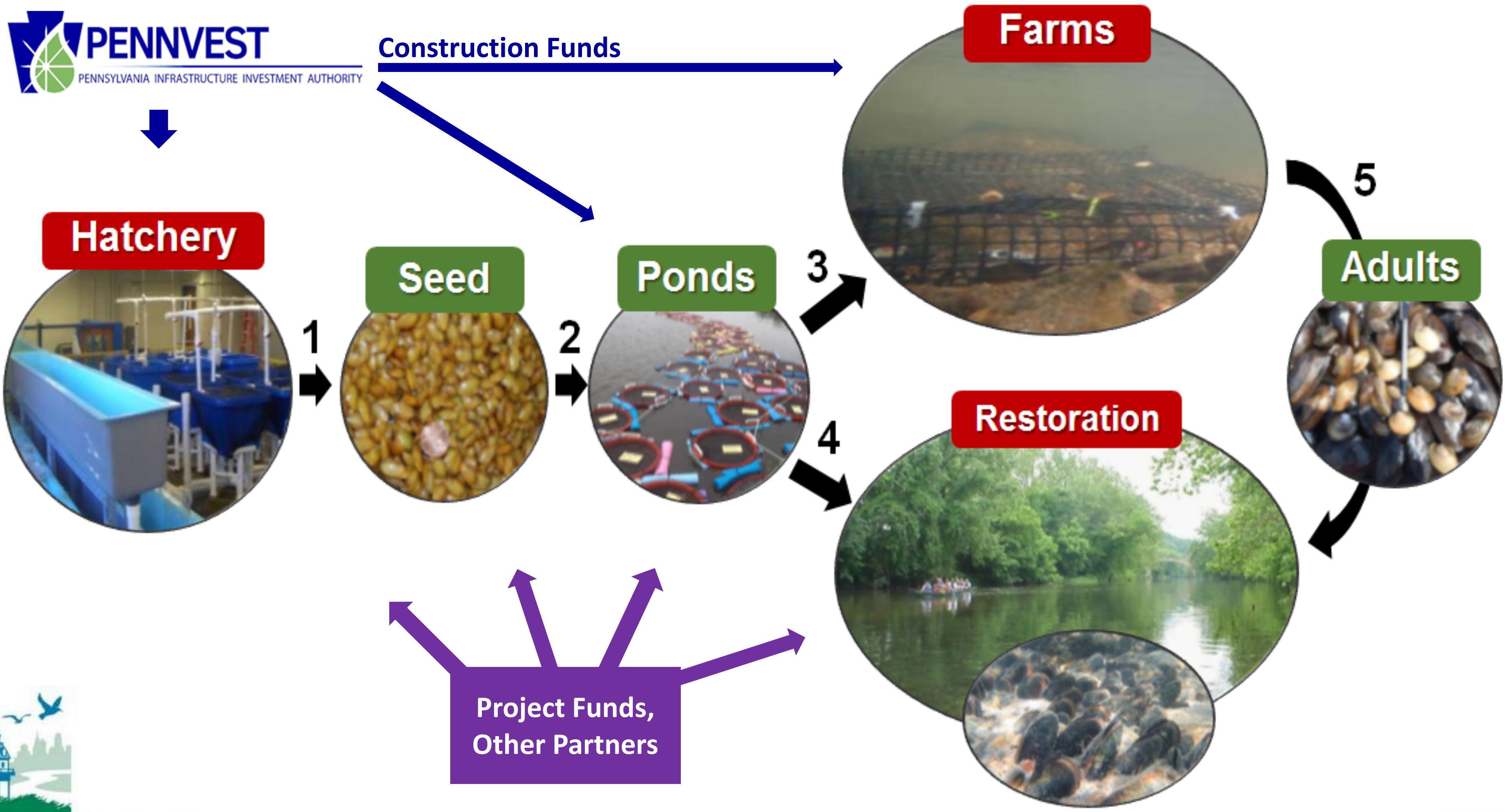
March Mussel Madness

Lincoln Financial Field, 3/21/19

THE MUSSELS FOR CLEAN WATER INITIATIVE

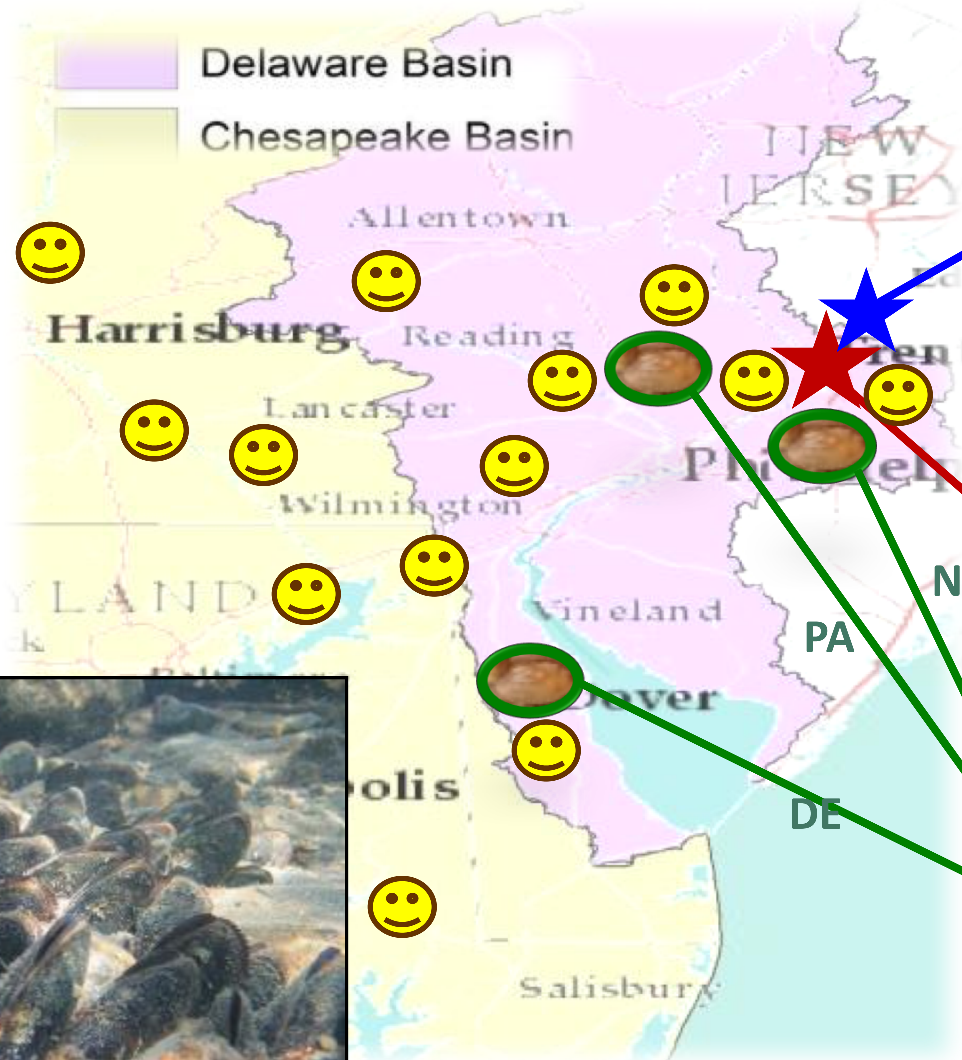
OF THE DELAWARE AND SUSQUEHANNA RIVERS

WATER QUALITY ENHANCEMENT BY BEDS OF FRESHWATER MUSSELS



Partnership for the DELAWARE ESTUARY

MuCWI Strategy (contingent on partners and $$)



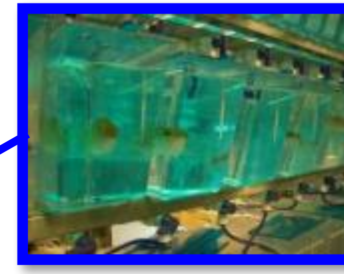


Exhibit Hatchery
(FWWIC, 2017)

Production Hatchery
(2023)

Pond Grow-Out

Restoration Targets

Summary

- Freshwater mussels filter as much water as oysters
- Most populations are in decline and deserve protection
- Ecosystem services by mussel *beds* (common and rare species) should be included in damage assessments and mitigation projects
- Restoring *all* native species can promote water quality
- Many opportunities exist for green investment
- Mussel projects should be vetted and based on science
- Funding for research and pilot projects has been difficult

Partnership for the DELAWARE ESTUARY

Partnership for the DELAWARE ESTUARY

Thank You!

Danielle Kreeger, Ph.D.
Science Director
(302) 655-990, x104 | DelawareEstuary.org

Connecting people, science, and nature for a healthy Delaware River and Bay

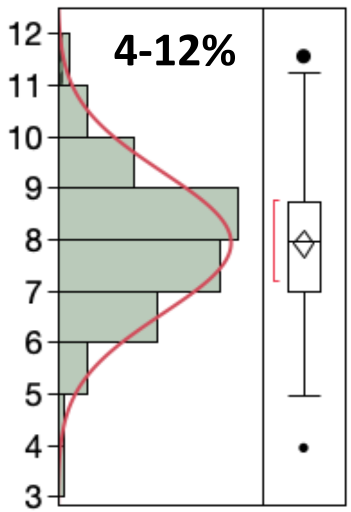
For More Info:

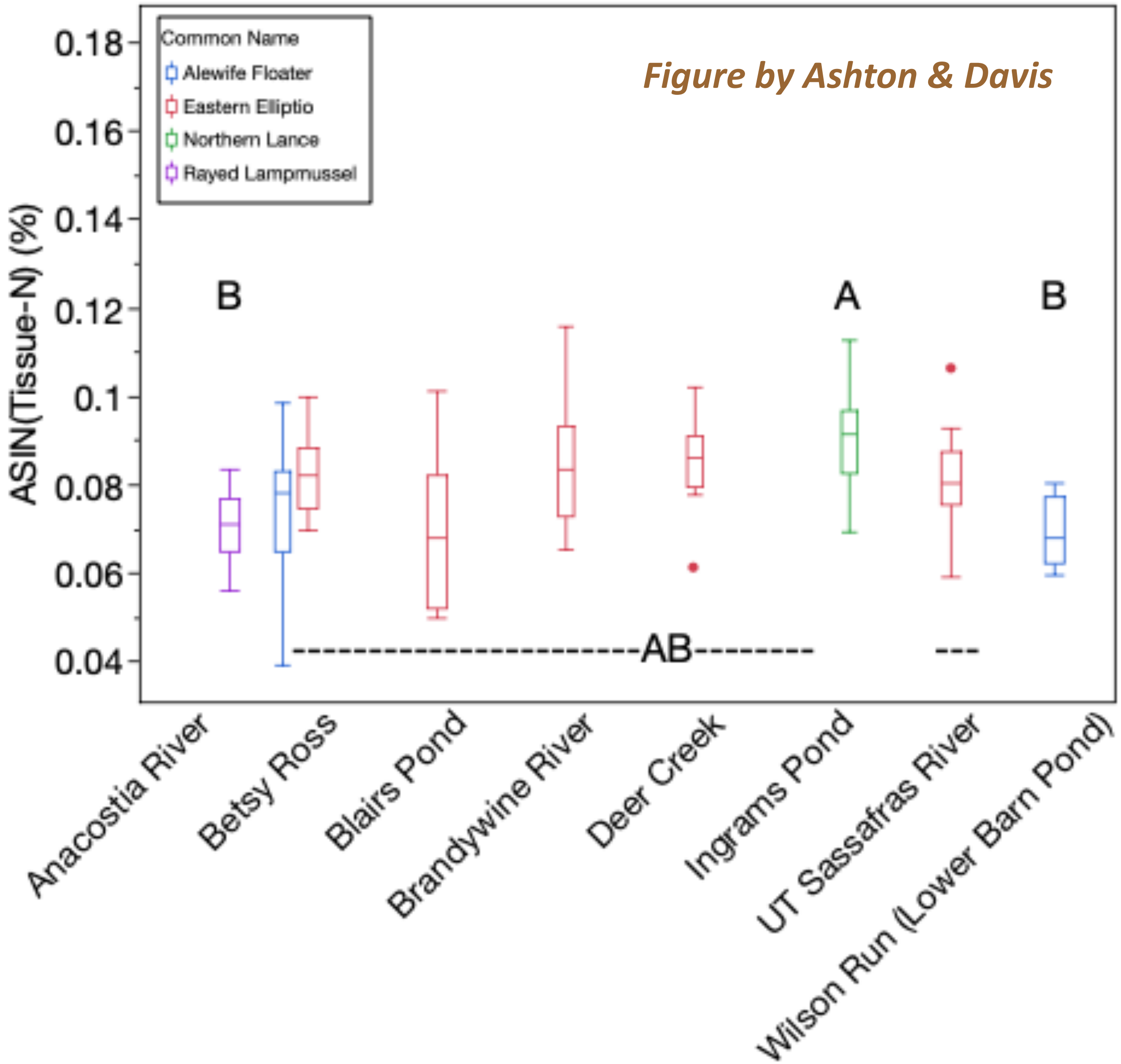
Mussels for Clean Water Initiative
http://www.delawareestuary.org/science-and-research/mussels-clean-water-initiative-mucwi/

Research – Nitrogen Removal Rates

N in Mussel Tissues and Shells

<u>In Progress by</u>
Matt Ashton, MD DNR
Megan Davis, MD DNR
Matt Gray, Univ of MD
Danielle Kreeger, PDE



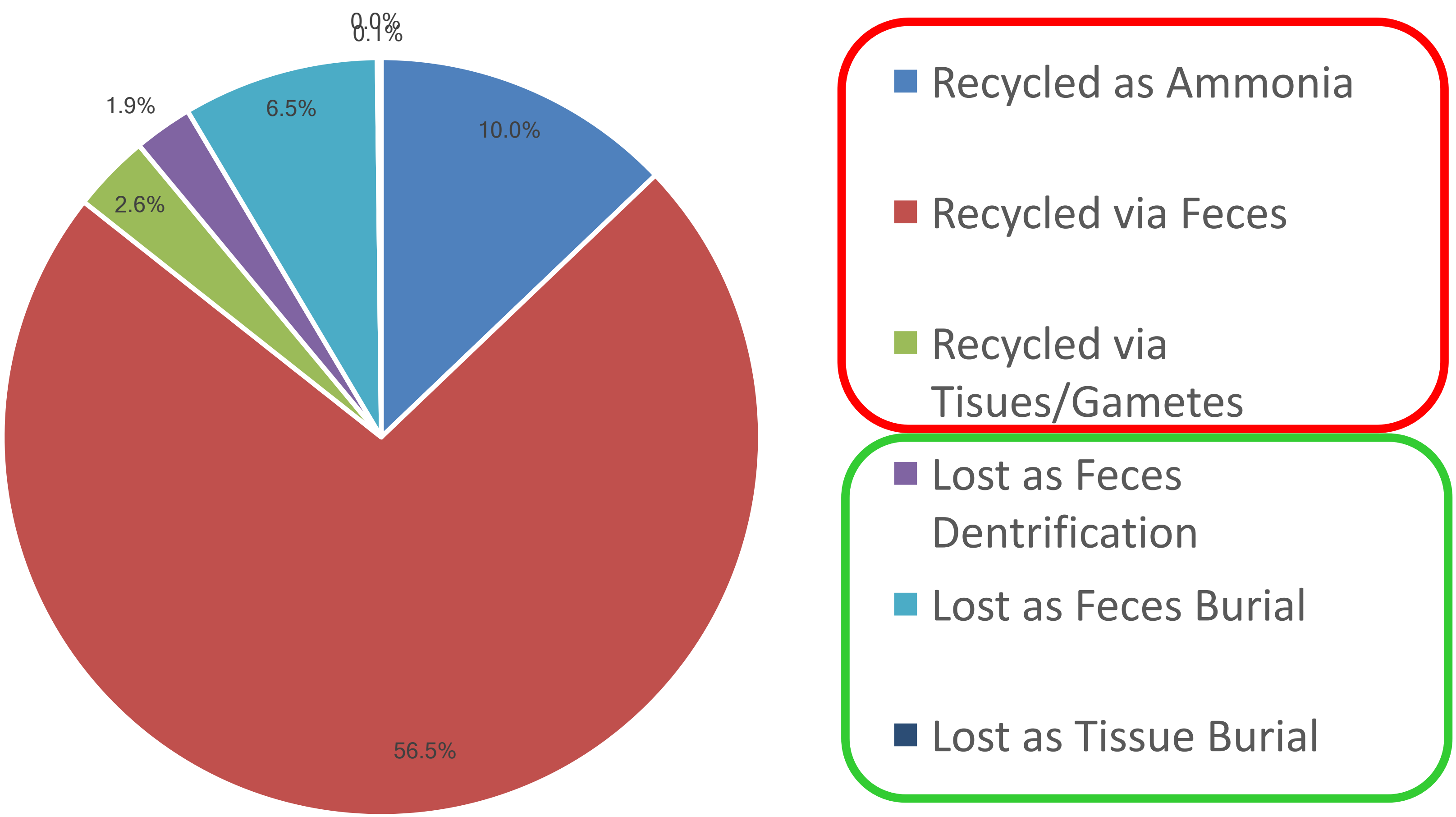


Water Quality Benefits?

Seston Pollutant Variability

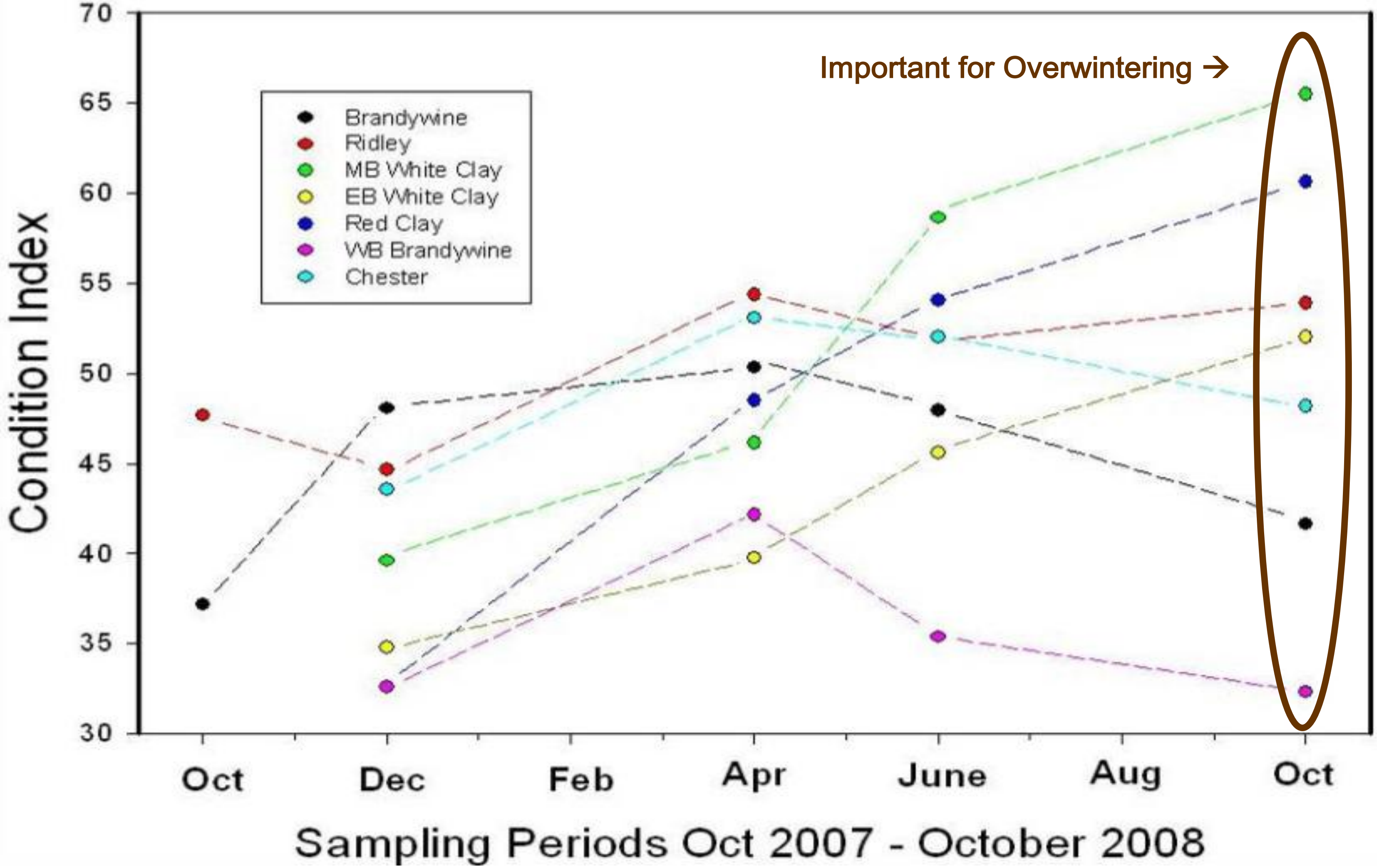
Area	Site	Sampling Time/n	TSS mg/L	POM mg/L	Organic %	Protein mg/L
FW Tidal Delaware River	Cherry Island, DE	n=53 (2009-2011)	27.6	5.3	20.2	1.3
	Eddystone, PA	n=51 (2009-2011)	15.8	3.5	22.9	1.1
	Betsy Ross, NJ	n= (2017)	9.8	2.4	25.4	*0.7*
Salt Marsh Tributaries	Dennis Creek, NJ	n-18 (2013-2014)	107.1	17.9	16.7	5.8
	Dividing Creek, NJ	n-18 (2013-2014)	71.3	10.2	14.3	3.3
	Maurice River, NJ	n-18 (2013-2014)	91.4	12.9	14.1	4.9
Delaware Bay Reefs	Elbow Crossledge	n=77 (2009-2011)	11.7	3.4	29.7	0.8
	Ship John	n=189 (2000-2014)	22.3	4.6	21.7	1.3
	Bennies	n=134 (2000-2014)	17.1	3.7	22.8	0.9

Gross versus Net Nutrient Removal



10,000 mussel seed over 30 years -> 729 pounds net N removal

Condition Index Over 1 Year



Gray & Kreeger 2014

Results – Absorption Efficiencies

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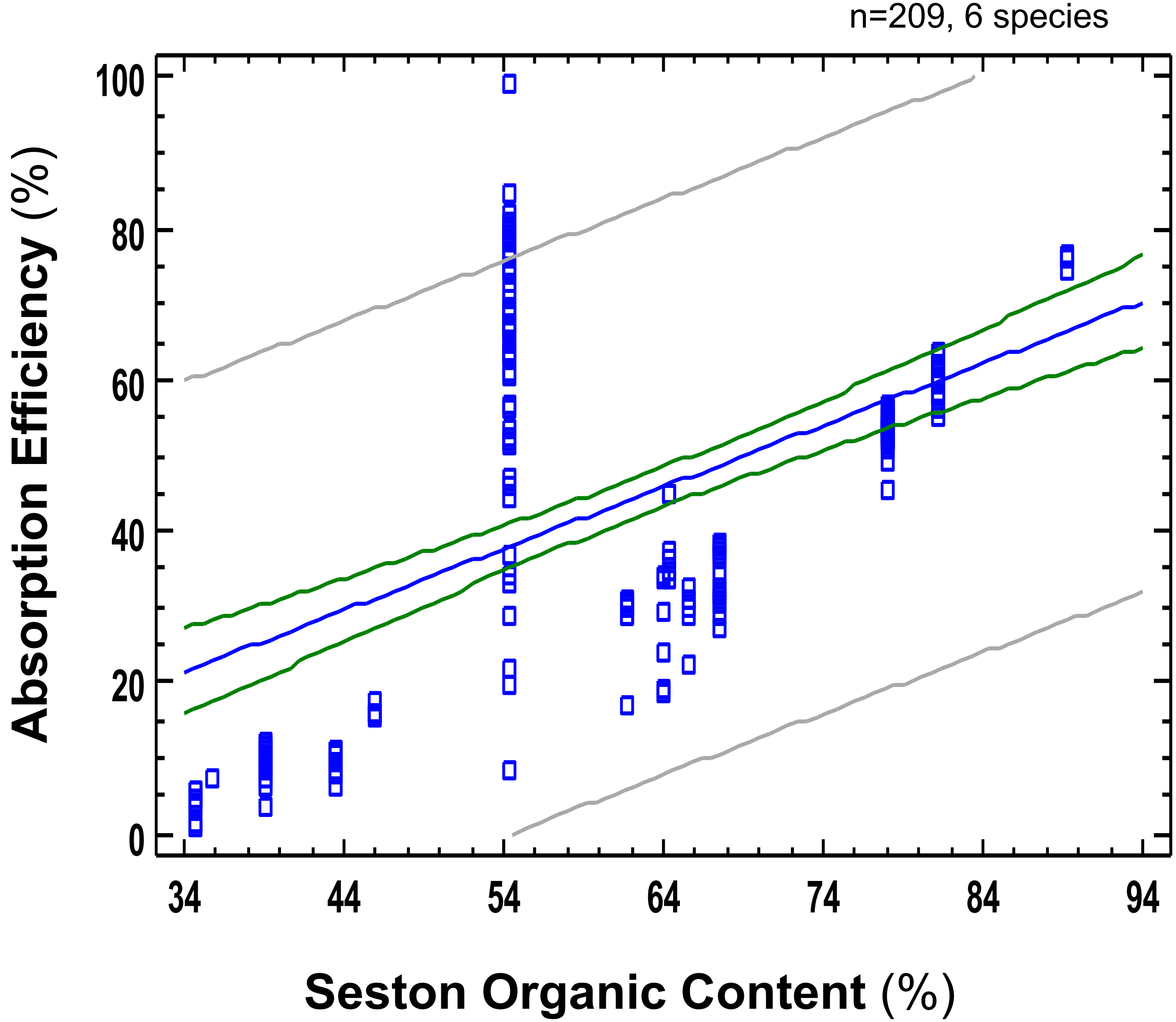
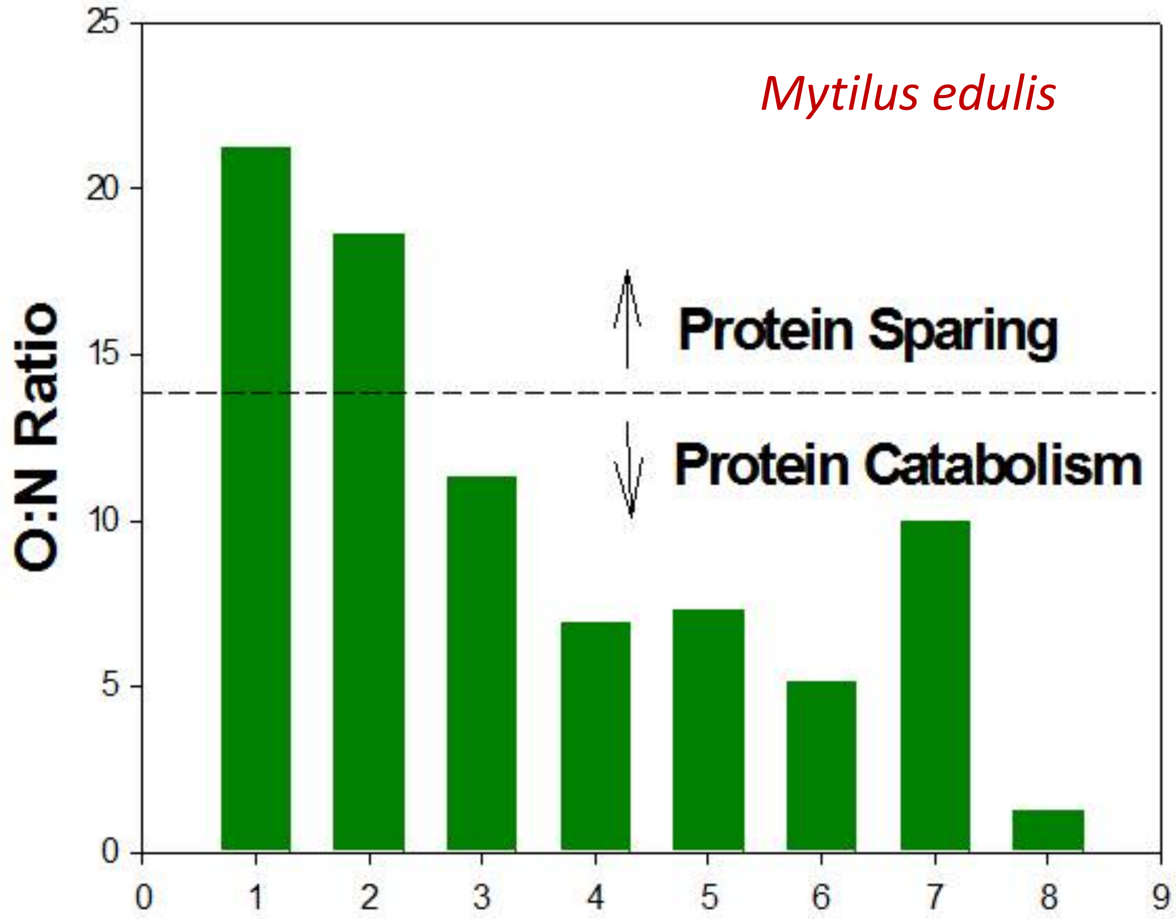
Utilization of filtered diets varies with food quality



Ammonia Excretion versus Nutritional Status

Bivalves likely remineralize more N in eutrophic waters

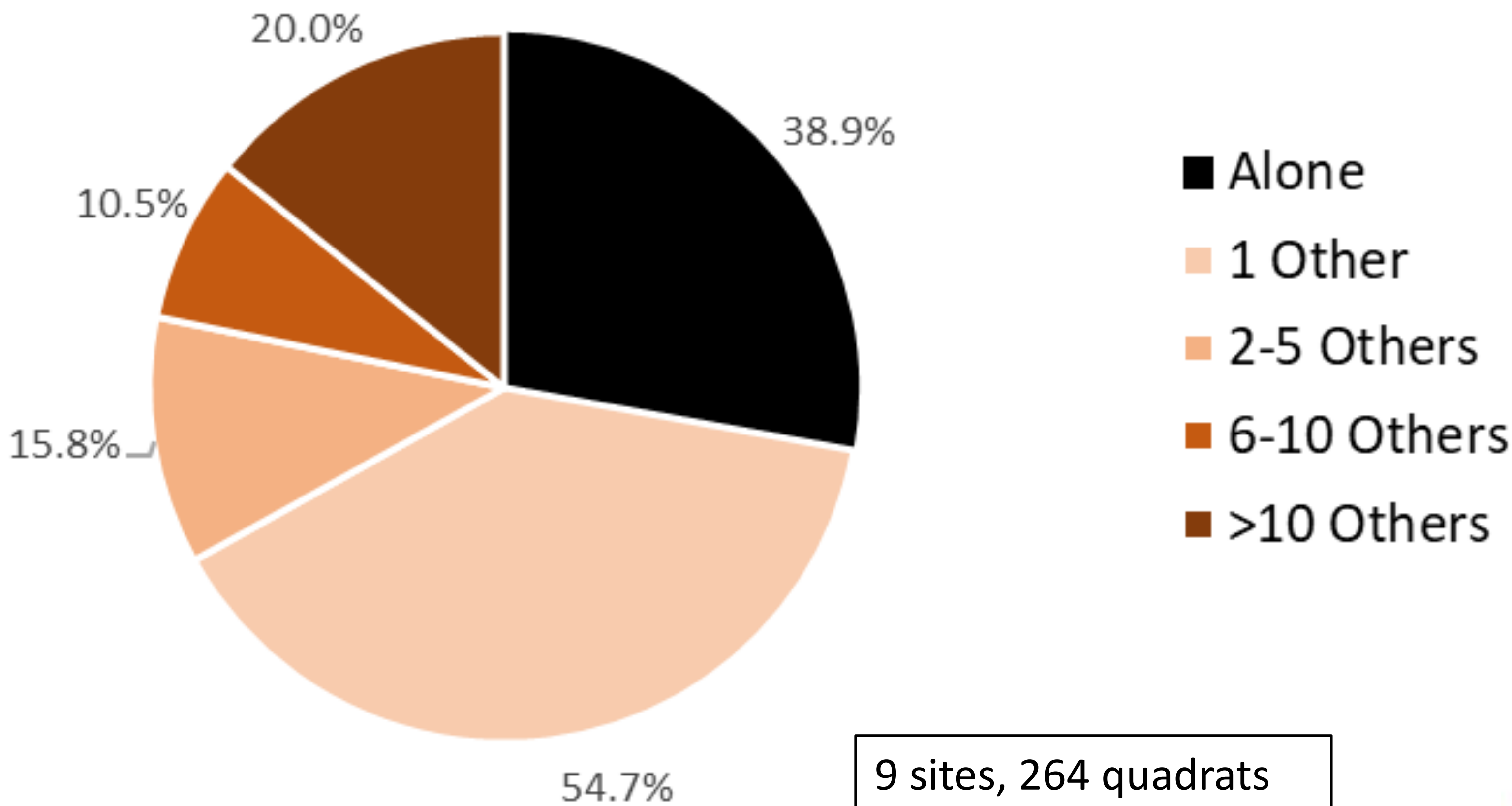


Bioavailable N in Seston→

Kreeger & Langdon 1993

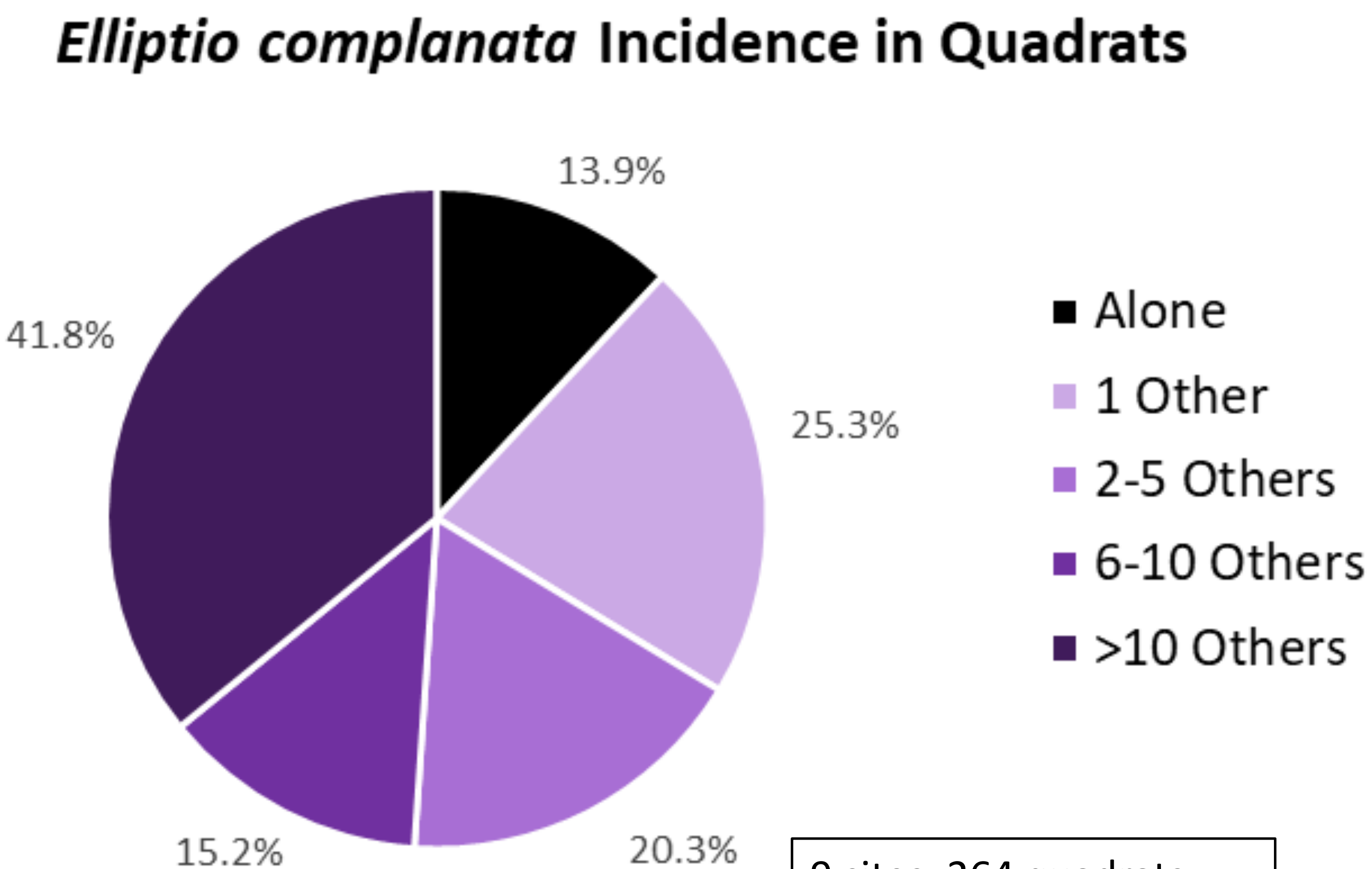
Why Common Species Focus?

***Utterbackiana implicata* Incidence in Quadrats**



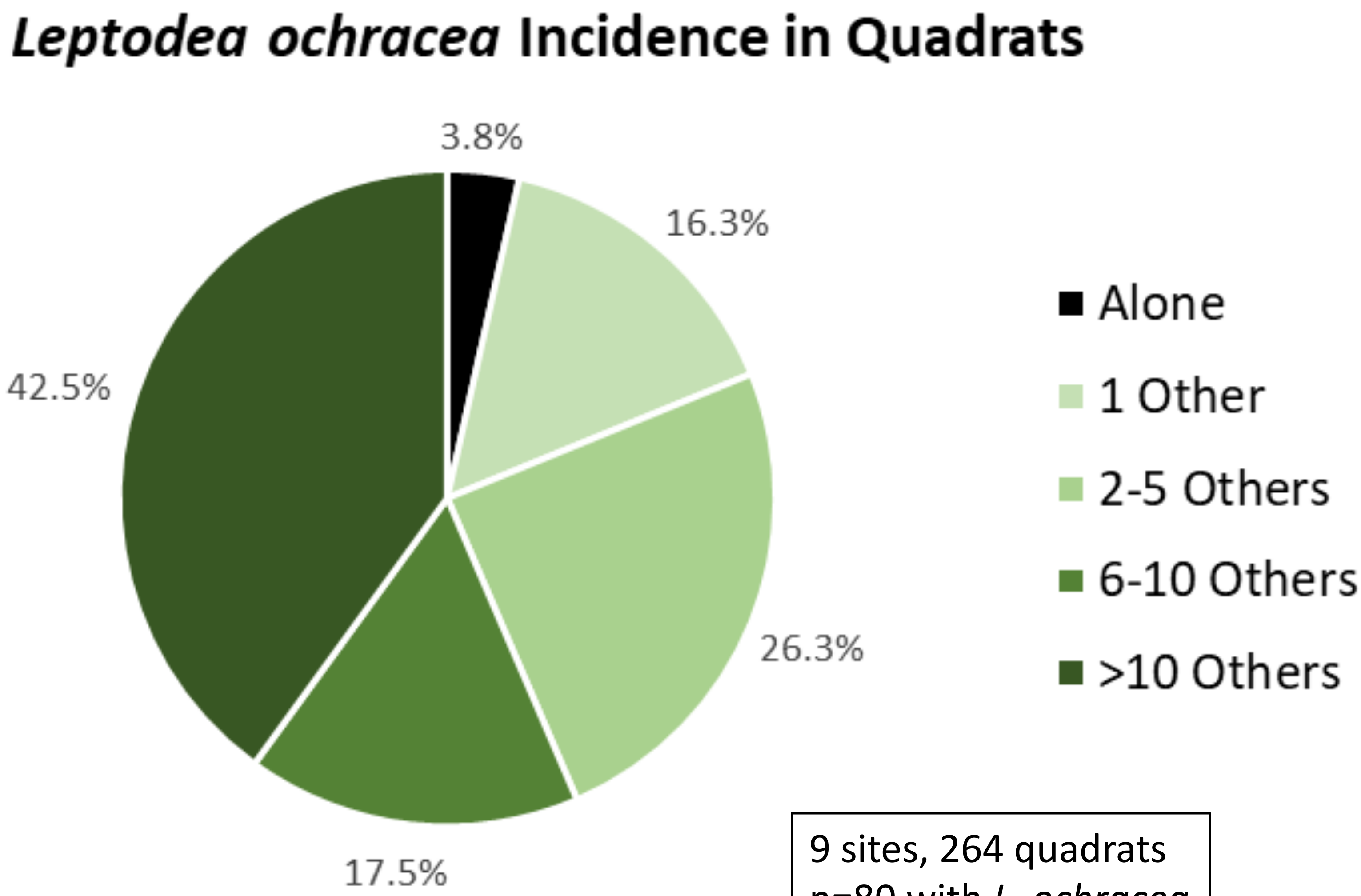
9 sites, 264 quadrats
n=95 with *U. implicata*

Why Common Species Focus?



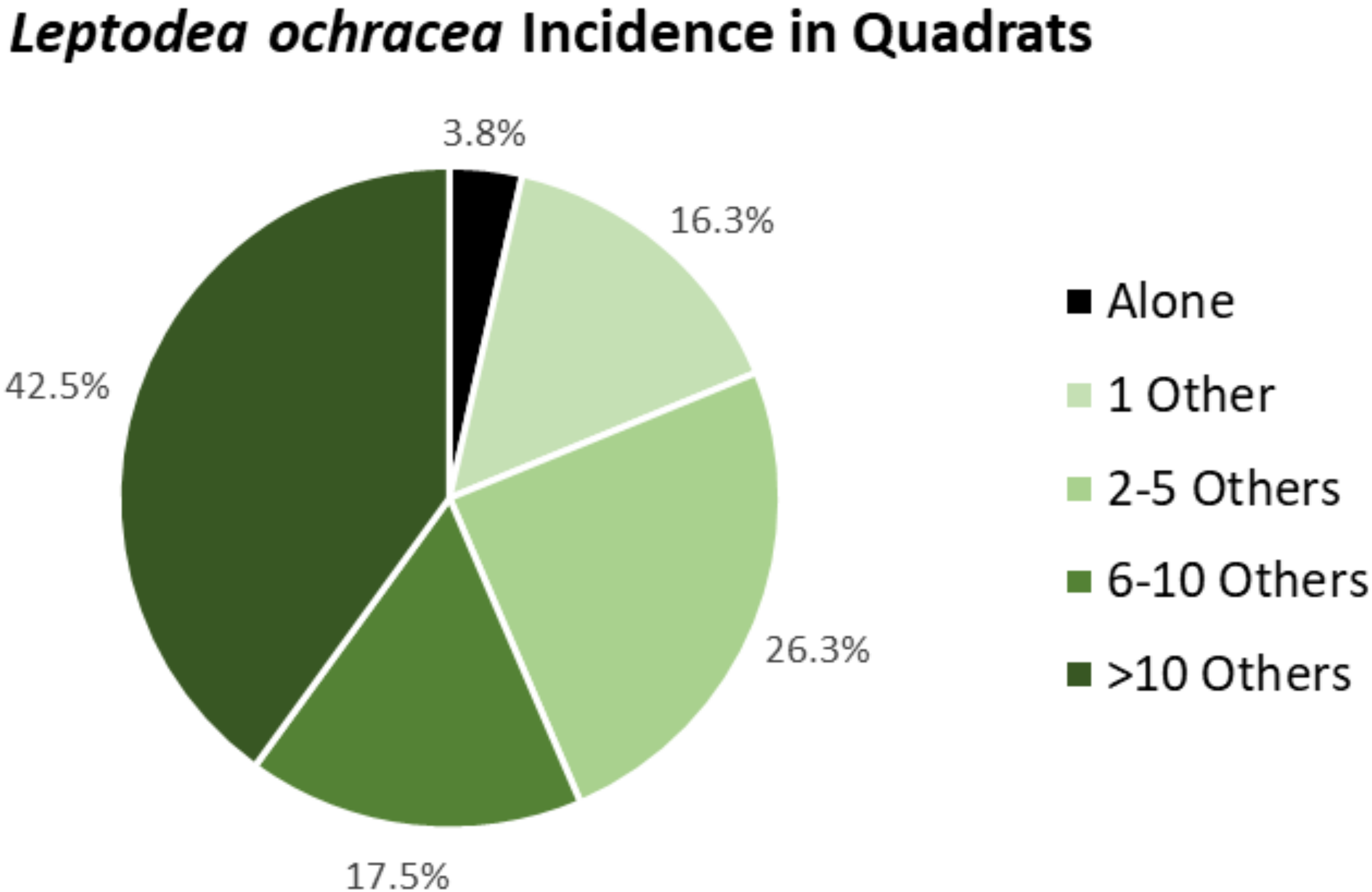
9 sites, 264 quadrats
n=79 with *E. companata*

Why Focus on Common Species?



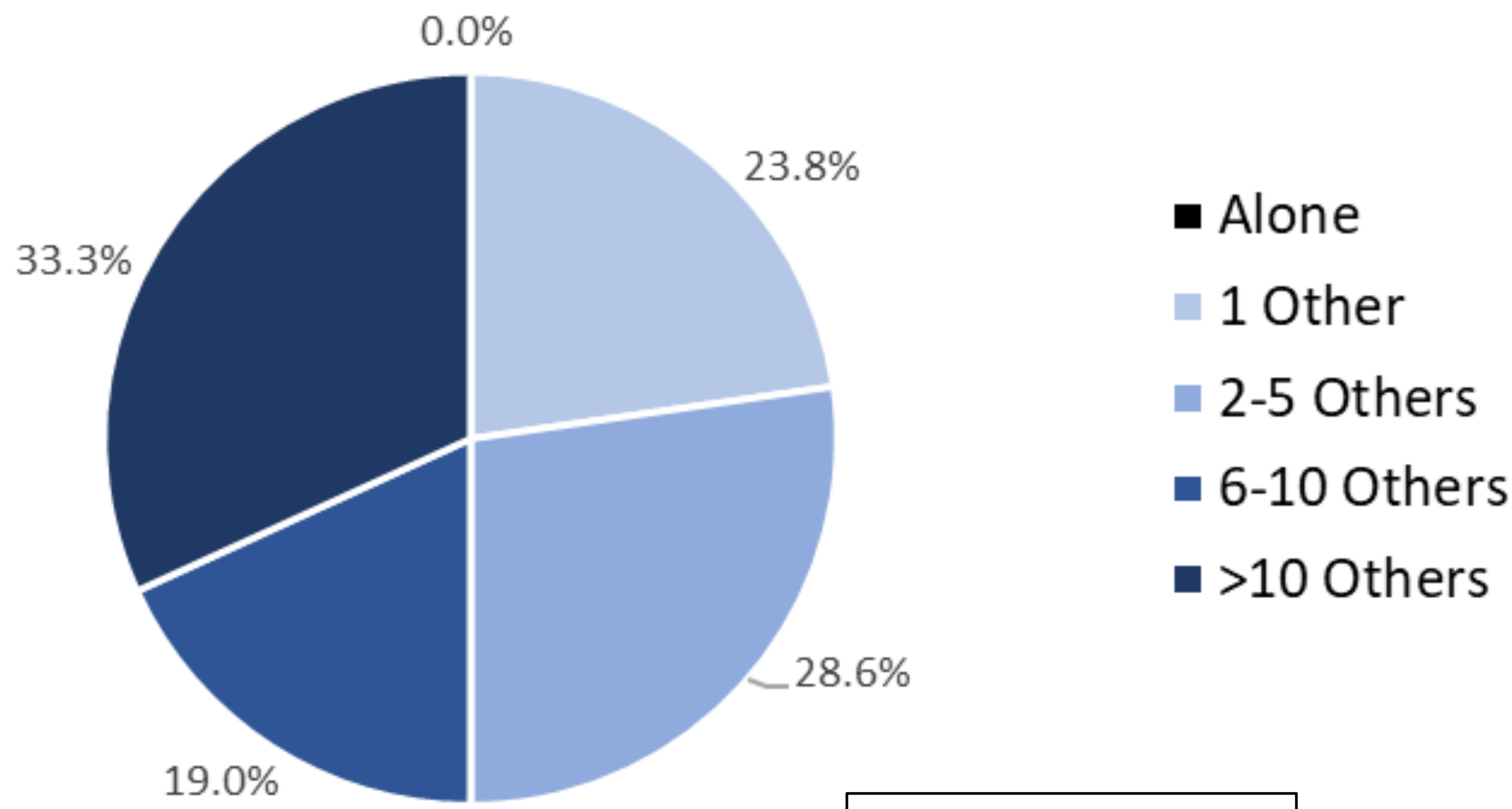
9 sites, 264 quadrats
n=80 with *L. ochracea*

Surveys – Tidewater Muckets *(Leptodea ochracea)*



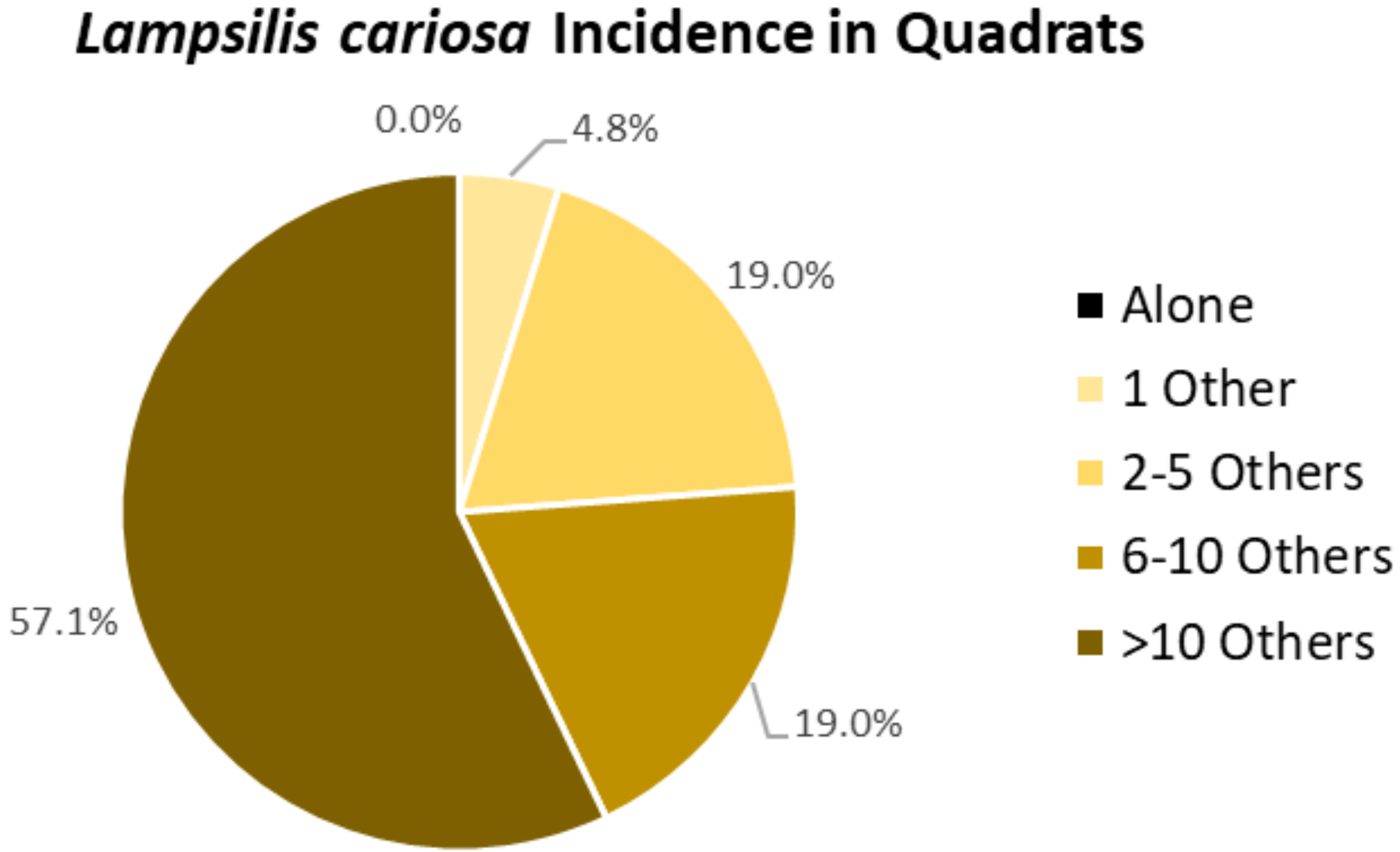
Why Common Species Focus?

***Ligumia nasuta* Incidence in Quadrats**



9 sites, 264 quadrats
n=21 with *L. nasuta*

Why Common Species Focus?



9 sites, 264 quadrats
n=21 with *L. cariosa*