

**Mid-Term Progress Report**  
**Plum Island Ecosystems LTER IV**  
**September 17-19, 2019**



D.S. Johnson photo



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## I. Site Description and History of Previous Work

The Plum Island Ecosystems (PIE) LTER site consists of a linked watershed-marsh-estuarine system located north of Boston, Massachusetts. PIE lies within the Acadian biogeographic province, a cold water environment sharing many species with boreal and Arctic provinces of the western Atlantic Ocean. Much of the biology at PIE is distinct from coastal ecosystems to the south of Cape Cod (Massachusetts) a historic geographic barrier for many species, although this is changing due to the rapidly warming waters of the Gulf of Maine.

The brackish and saline tidal wetlands of the PIE site form the major portion of the “Great Marsh”, the largest contiguous acreage of intact marsh on the northeast coast of the United States. The coastal system is macrotidal –with tidal excursions often exceeding 3 meters. The marshes and the estuarine waters are influenced by three rivers: the Ipswich, the Parker and the Rowley, which collectively drain over 550 km<sup>2</sup> of upland (Fig 1).

### History of Previous Research

The Plum Island Ecosystems LTER has, since its inception in 1998, been working towards a predictive understanding of the long-term response of coupled land-marsh-estuary-ocean ecosystems to changes in three key drivers: climate, sea level and human activities.

In PIE I we asked “*How will trophic structure and primary and secondary productivity in estuaries be affected by changes in organic matter, nutrient, and water fluxes caused by changing land cover, climate, and sea level.*” During PIE I we established long-term monitoring activities and carried out a number of experiments in the contrasting Parker and Rowley river estuaries to address this question. These revealed that hydrology played an enormous role in structuring the food web by altering residence times. Pelagic phytoplankton dominate primary production in the high residence time, more turbid Parker estuary, while benthic production dominates in the shallow, more rapidly flowing Rowley estuary. These differences in primary producers cascade throughout the food web.

During PIE I we made substantial progress understanding how accelerated sea-level rise impacts marsh processes. We found that marsh grass production in PIE and South Carolina responded similarly to changes in relative sea-level rise (SLR), despite the marshes being fundamentally different in structure (peat vs mineral). This link between relative SLR and marsh productivity led to a generally applicable Marsh Equilibrium Model of marsh response to SLR.

In PIE II we focused more heavily on the importance of the interactions of changing nutrient, water, and organic matter inputs within the “*hydrologic and geomorphic template*” (e.g., places where residence time was always short, and others where it was seasonally long). We quantified how hydrology controls N cycling both in the watershed and in the estuary through its impact on estuarine salinity and C and N inputs. We found hydrology structures both pelagic microbial communities as well as microbes in the sediment. In the estuary, hydrodynamics affects water

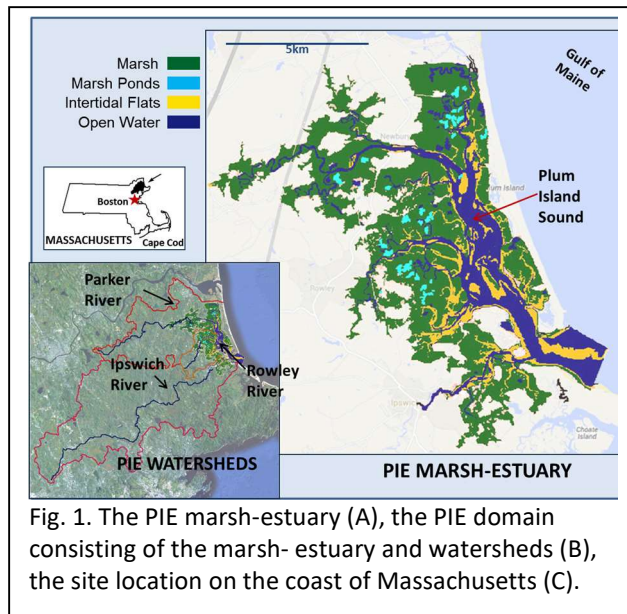


Fig. 1. The PIE marsh-estuary (A), the PIE domain consisting of the marsh- estuary and watersheds (B), the site location on the coast of Massachusetts (C).

column metabolism through creek bank drainage, which is an important source of carbon supporting estuarine water column respiration. Interactions between nutrient delivery, marsh grass production, and food web responses were examined in a large-scale marsh creek-shed experiment (TIDE; Deegan et al. 2007).

During PIE II it became evident that we had to incorporate *geomorphic change* into our conceptual model. We documented substantial changes in the abundance and distribution of vegetation, ponds, and creeks throughout the marsh and estuary. Human actions that altered river flow were impacting estuarine salinity regimes and the forms and quantities of nutrients delivered from the watershed.

PIE III directly addressed how geomorphic change shapes organic matter and nutrient transformations in linked watershed and coastal ecosystems. Our goal for PIE III was *to understand how external drivers, ecosystem dynamics, and human activities interact to shape ecological processes in a mosaic of coastal landscapes and estuarine seascapes*. This framework was designed to: (1) examine linkages and feedbacks between watersheds, marshes, estuaries, and the coastal ocean in more detail; (2) identify the role of geomorphology and geomorphic change on ecosystem processes, and understand how ecosystem processes alter geomorphology; and (3) incorporate the human dimension in a dynamic way. This evolution in focus allowed us to begin a broader synthesis between our program areas. The impact of *temporal change and variability* on ecological processes was addressed through long-term monitoring.

## II. PIE IV Focus and Goals

The focus of PIE IV is *Dynamics of coastal ecosystems in a region of rapid climate change, sea-level rise, and human impacts*. In this cycle, we are putting a greater focus on topics that emerged as critical areas in PIE III, including sediment dynamics, species interactions, and the role of ocean warming on species changes. We have continued to examine how external drivers alter the geomorphology, biogeochemistry, and population and community ecology of coastal ecosystems, however, we are putting more emphasis on the feedbacks between geomorphology, biogeochemistry, and communities. In keeping with the change in the LTER program we removed the human dimension from the core LTER but pursued these questions through a cross-LTER Coastal SEES project.

PIE is currently dominated by high elevation marshes (Fig.2). We proposed that there will be large changes in the geomorphology of the marsh and estuary over the next century that will move PIE from a predominantly high-elevation marsh system dominated by *Spartina patens* to a lower elevation, more frequently

flooded marsh dominated by *S. alterniflora*. We also proposed that we will eventually see more open water and marsh edge when marshes can no longer migrate inland due to steep elevation gradients or human structures. This trajectory of geomorphic change is largely driven by

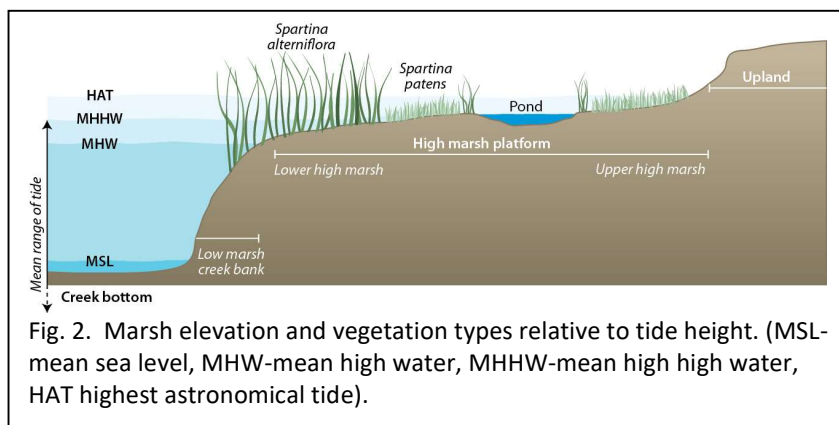


Fig. 2. Marsh elevation and vegetation types relative to tide height. (MSL-mean sea level, MHW-mean high water, MHHW-mean high high water, HAT highest astronomical tide).

external drivers, especially sea-level rise (SLR) and climate change, but highly modified by internal feedbacks and, potentially, by human activities. We have since refined our model of change to acknowledge that the “transition” from high marsh to low marsh may proceed at a different time scale than the overall “squeeze” of marshes along the upland boundary (Fig. 3). Both marsh “transition” and “squeeze” will have important impacts on marsh productivity, community structure, and biogeochemistry.

The PIE IV conceptual model examines the dynamics and interactions between the geomorphology, biogeochemistry, and ecological structure and function of the Plum Island marsh-estuary in response to the three external drivers: sea-level rise (SLR), climate, and human activities (Fig 4). This conceptual model led to the three major questions in the current proposal as well as three hypotheses relating to each question (detailed below). The justification for these questions and hypotheses, as well as more information on the changing drivers, can be found in the first 5 pages of our proposal.

Because we predict the marsh will transition fairly rapidly in the coming decades,

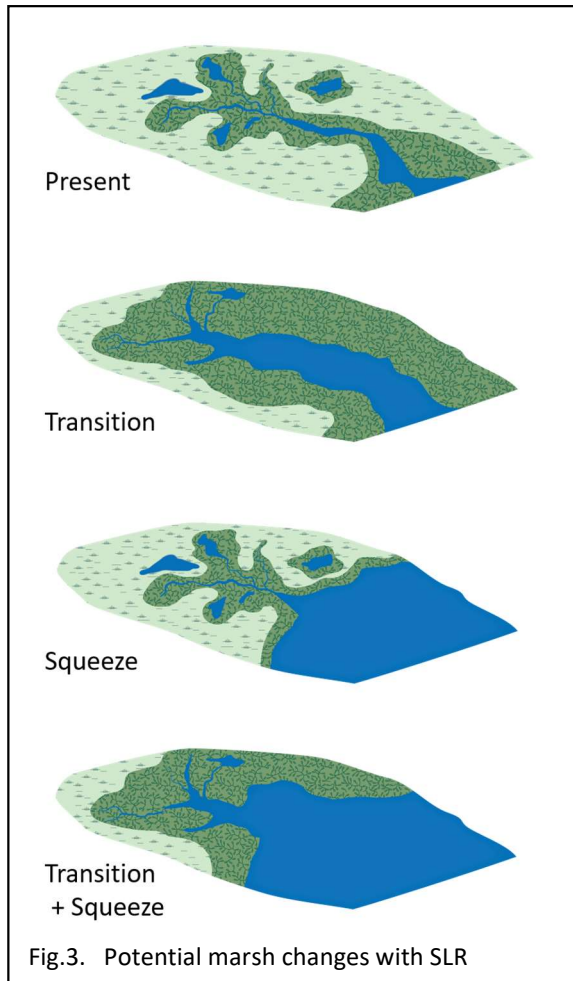


Fig.3. Potential marsh changes with SLR

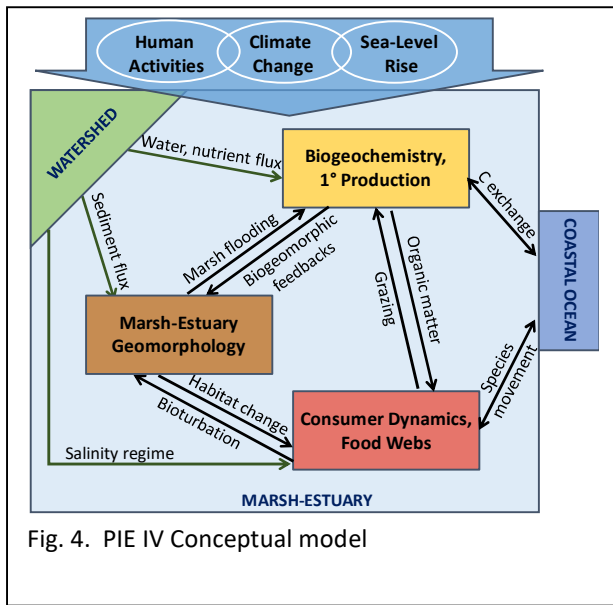


Fig. 4. PIE IV Conceptual model

PIE IV is using an intensive and comprehensive “space-for-time” approach to compare low-elevation, *Spartina alterniflora* marsh areas to higher elevation *S. patens* marsh areas (Fig. 5).

We are monitoring both the tidal creeks and associated “creeksheds” to address multiple research questions and hypotheses focused on understanding the changing geomorphic configuration of the marsh (H1.3), how changes in marsh geomorphology interact with changing watershed inputs, climate, and sea level to affect marsh (H2.1) and estuarine (H2.3) biogeochemistry, and how populations, communities, and food-web structures will respond to these changes (H3.1). As detailed below, we have made significant progress in the first three years of this LTER renewal in understanding how ecosystem processes in the low-elevation and high-

elevation marshes differ, which will inform our ability to predict ecosystem-scale alterations to the Plum Island system with climate and land-use change.

In addition to work at PIE, cross-system comparisons with other LTERs along gradients of temperature, species composition, tidal range, and sediment supply are leading to a broader mechanistic understanding of long-term change in coastal ecosystems.

### III. Questions and Hypotheses

**Q1) How will the geomorphic configuration of the marsh and estuary be altered by changes in the watershed, sea-level rise, climate change, and feedbacks internal to the coastal system?**

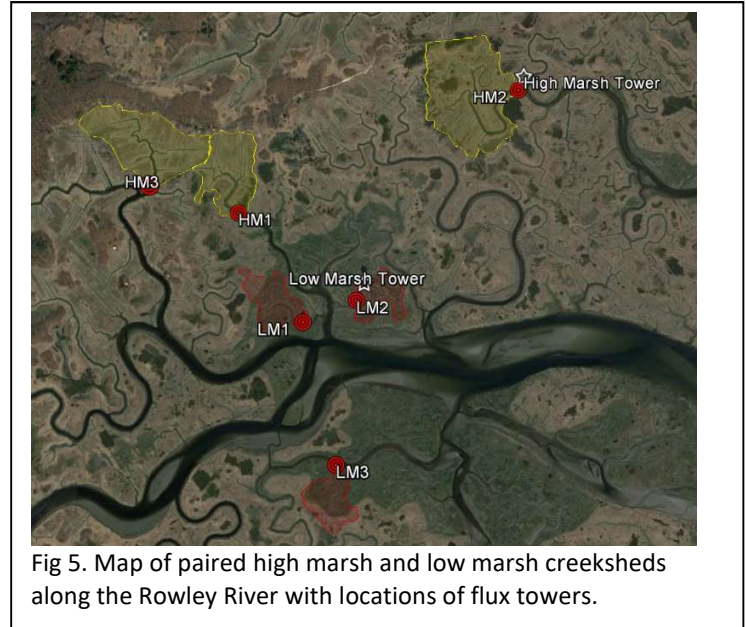


Fig 5. Map of paired high marsh and low marsh creeksheds along the Rowley River with locations of flux towers.

*H 1.1) Sea-level rise and climate change will lead to an increase in the lateral erosion of marshes.*

In order to determine the evolution of salt marshes in Plum Island Sound and whether sea-level rise will increase lateral erosion, we first must determine if the marsh is currently eroding, expanding, or keeping pace with sea-level rise by estimating a sediment budget for the sound (Ganju et al. 2017). Using PIE-LTER long-term datasets we computed a budget for the entire marsh/estuarine system, showing that marsh edge erosion provides an important fraction of the material needed for marsh accretion, such that, and because of limited external sediment supply, the marsh platform maintains elevation at the expense of total marsh area (Fig. 6). To better understand the sediment fluxes within the system, we used the high resolution numerical model Delft3D (Zhang et al. 2019a). Numerical simulations showed that most sediment discharged into Plum Island Sound from tidal rivers is deposited in shallow tidal flats and channels and is unable to penetrate farther inside the marshes because of limited water depths and velocities on the marsh platform. So although some sediment is deposited in the adjacent marshes, deposition decreases exponentially with distance from the channels and marsh edge.

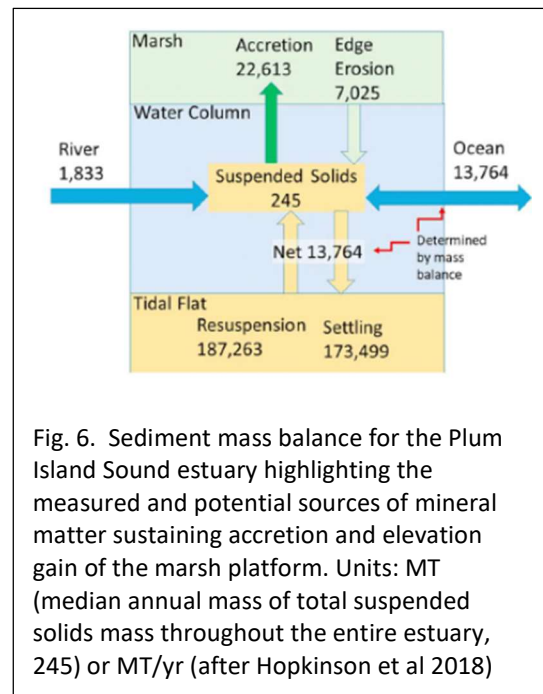


Fig. 6. Sediment mass balance for the Plum Island Sound estuary highlighting the measured and potential sources of mineral matter sustaining accretion and elevation gain of the marsh platform. Units: MT (median annual mass of total suspended solids mass throughout the entire estuary, 245) or MT/yr (after Hopkinson et al 2018)

Long-term records of the flow of water through tidal channels are essential to constrain the budgets of sediments and biogeochemical compounds in salt marshes but difficult to model. We have developed four different types of stage-discharge models, each of which captures different

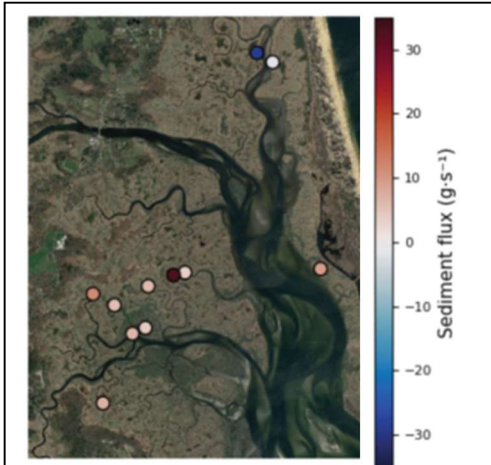


Fig. 7. Sediment budgets of 11 salt marsh complexes measured over two months. The color of each point represents the magnitude and direction of the net sediment fluxes.

characteristics of the stage discharge relationship (Kearney et al. 2017). These models were applied to eleven salt marsh complexes on 2-month long time series of stage and discharge (Fig. 7). Sediment fluxes in salt marsh channels within a single estuarine marsh complex vary in both space and in time. This variability is driven by the supply of sediment and by the hydrodynamics of the marsh channel and also changes temporally over the spring-neap tidal cycle and with changes in external forcing (Kearney 2018).

Lateral erosion can occur when muddy banks of marshes experience slumping – a slow deformation resulting in a net downslope transport – but the cause is not well understood. We have measured soil slumping in Plum Island Sound using both marker-pole displacement and high precision ( $\pm 0.03$  mm) measurements of soil deformation taken with a vibrating-wire extensometer (Mariotti et al. 2019). High precision measurements shed light on the erosion of salt marsh banks. First, the low

bank compressed and extended by  $\sim 5$  mm/m every tidal cycle, suggesting that the diurnal changes in water level played a role in bank movements. Second, net soil extension, or “creep”, took place mostly during fall, and preceded ice formation, suggesting that freezing and ice rafting were not a leading cause. Instead, net soil extension was likely triggered by an increase in water table during fall, which destabilized the bank. This high water table was caused by a combination of an increase in atmospheric precipitation and a decrease in evapotranspiration triggered by vegetation senescence. This study confirmed that creep is a significant process in marsh morphodynamics and that vegetation can reduce erosion of marsh banks. We have now developed a numerical model for soil creep in salt marshes (Mariotti et al. 2016) that suggests bank slumping is a natural feature that does not necessarily indicate marsh loss nor do high sedimentation rates on channel banks necessarily indicate resilience to accelerated SLR.

The final step to determine the effect of sea level rise on marsh erosion is to understand the feedback between SLR and intertidal geomorphology. A set of model simulations show that SLR increases tidal prism and inundation depth, facilitating sediment deposition on the marsh platform (Zhang et al. 2019c). At the same time, SLR enhances ebb-dominated currents and increases sediment resuspension, reducing the sediment-trapping capacity of tidal flats and bays. The amount of sediments exported from the bay to the ocean overcomes that deposited on the marsh platform, leading to a negative sediment budget for the entire system (Fig.8)

Next Steps - Currently we are using simulations of erosion and deposition to distinguish the differential sensitivity of the sand and fine fractions to SLR to examine net sediment transport.

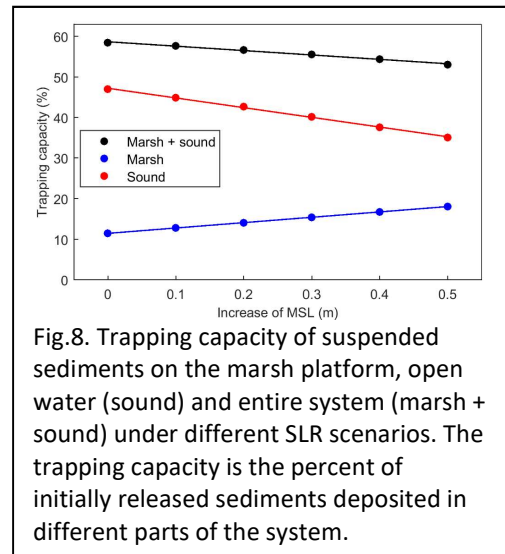


Fig.8. Trapping capacity of suspended sediments on the marsh platform, open water (sound) and entire system (marsh + sound) under different SLR scenarios. The trapping capacity is the percent of initially released sediments deposited in different parts of the system.

This is important as sediment export would increase the depth of the bay, triggering higher waves and more erosion at the marsh boundaries.

**H 1.2) Removal of human dams, and increased variability in precipitation, will increase sediment mobilization within the watershed and sediment export to the estuary.**

PIE watersheds are in the process of transitioning from being dominated by human reservoirs along river mainstems, to beaver ponds in the headwaters. At the same time, population continues to grow and suburban land use continues to intensify, while climate variability is projected to increase. All of these drivers potentially affect sediment dynamics, and we are focused on understanding how sediment fluxes to the coastal marshes will be affected. To more directly address the role of reservoirs and climate variability in sediment fluxes, over the past three years we have begun to: 1) quantify suspended sediment concentrations throughout individual storm events in both headwaters and along larger rivers; 2.) quantify TSS input and output budgets in a reservoir scheduled for removal and in several others in the region, as well as in one beaver pond active since 2005; 3) added a TSS module to our river network modeling system, the Framework for Aquatic Modeling in the Earth System (FrAMES).

Despite long-term increases in precipitation, during the last decade there has been a decrease in total precipitation, leading to decreasing runoff (discharge). Consequently, TSS concentrations have decreased at all our sites. Since 2016, concentrations have stabilized, and are generally ~5mg/L higher in headwater streams than in the main stems. This difference suggests retention of TSS by the river network. However, our area-weighted fluxes (concentration/area-weighted discharge) are similar in headwaters and at the basin mouths, providing little evidence of retention (Fig. 9). Further, in contrast to expectations of differences in TSS export related to land use, fluxes from forested and urban catchments have not shown a difference. We think there are two possible reasons our data thus far do not show retention:

1.) We have missed high discharge events in our headwater sampling, so our sediment flux estimates are low; 2.) We have not accounted for a change in form of TSS from inorganic (clastic) to organic sediments during transit downstream. We have already adjusted our sampling to address both.

Headwaters streams have much flashier hydrographs compared to the mainstem rivers, so it is likely we have inadequately captured storm event TSS loading in the headwaters.

Recent measurements made during storm events show much higher storm event concentrations in the urban headwater (max = 175 mg L<sup>-1</sup>) compared to the forested headwater (53 mg L<sup>-1</sup>) or the mouth of the Parker and Ipswich Rivers (max = 13 mg L<sup>-1</sup>). These preliminary values are based on a limited number of storms, but if the differences

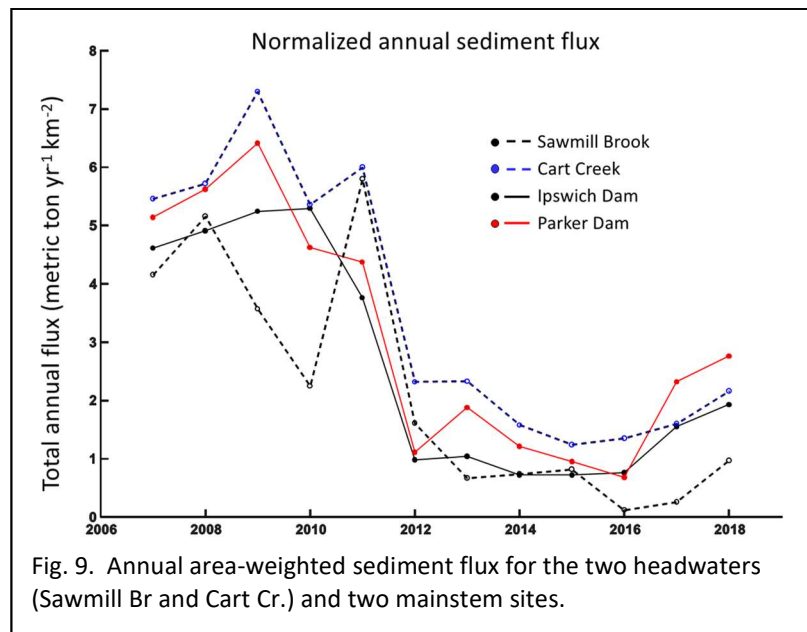
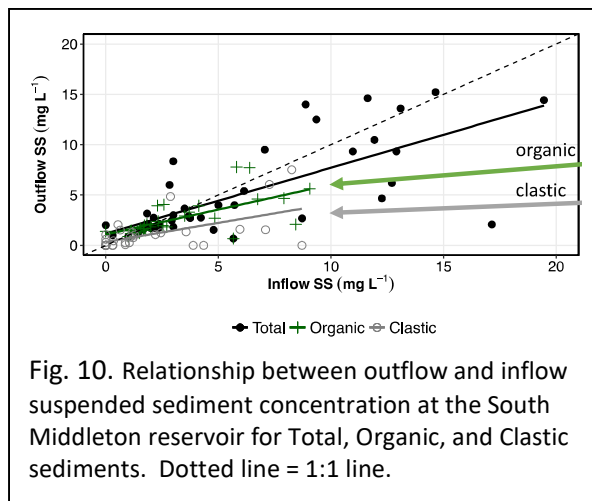


Fig. 9. Annual area-weighted sediment flux for the two headwaters (Sawmill Br and Cart Cr.) and two mainstem sites.



hold with further measurements, it suggests our current estimates of sediment loads to the river network in headwater streams (Fig. 9) are too low, creating an underestimate of sediment retention by the river network. These measurements also show climate variability, through its effects on discharge and TSS concentrations, is an important driver of sediment fluxes to the estuary.

Second, the composition of suspended sediments may be changing from more inorganic to more organic as water flows from headwaters, through reservoirs, to the basin mouth. Input-output budgets for one of the mainstem reservoirs in the PIE watersheds indicate it is a moderate net TSS sink, more so for inorganic than organic sediments (Figure 10). Inorganic TSS that is deposited is replaced by new organic TSS, attributable to summer algal production in the reservoir itself, thus masking the strength of the of inorganic TSS sink within the reservoir. It is likely this organic TSS is not transferred far downstream as this labile energy source enters the food web. This pattern of inorganic sink and organic source is also reflected in the nitrogen budget (see H 2.2).



**H 1.3) Sea-level rise will lead to a conversion of high elevation marsh to low elevation marsh, and a decrease in overall marsh area**

We are addressing this hypothesis by integrating long-term observations and modeling. Long-term observations include measurements in control and fertilized plots of 1) annual primary production of the two dominant saltmarsh species (*Spartina alterniflora* and *S. patens*), and 2) marsh surface elevation with Sedimentation Erosion Tables (SET) installed in the saltmarsh communities. In addition, a number of ancillary observations complement the long-term measurements, including 1) a study of the life-history of blocks of marsh (termed marsh bergs) that calve off the edges of creekbanks and deposit at different elevations in the tidal creeks, 2) marsh bioassay experiments (marsh organ) designed to establish the growth response of *Spartina* spp. to relative elevation, 3) a spatial survey of marsh biomass at different elevations, 4) an analysis of remote imagery and lidar elevation to establish vertical ranges of *Spartina* spp., 5) sediment accumulated on ceramic plates, and 6) a decomposition experiment with birch dowels to determine the depth distribution of decay rate in fertilized and control sites.

The empirical observations are informed by theory with the dual objectives of testing the theory behind the Marsh Equilibrium Model (MEM) and improving model parametrization. The one dimensional or ‘point’ version of MEM computes vertical accretion as a mass balance of mineral sediment and root inputs and decay. It incorporates feedbacks among vegetation, sediments, and tides that predict how a marsh could track sea level, within limits (Morris et al. 2002). Relative marsh elevation, a function of the rate of SLR, together with marsh productivity determine the rate of vertical accretion (Fig. 11). The original model (Morris et al. 2002) has been modified to incorporate variables that explicitly define processes that contribute to soil volume, such as below-ground biomass accumulation and the self-packing densities of organic and inorganic material in the soil (Morris et al., 2016).

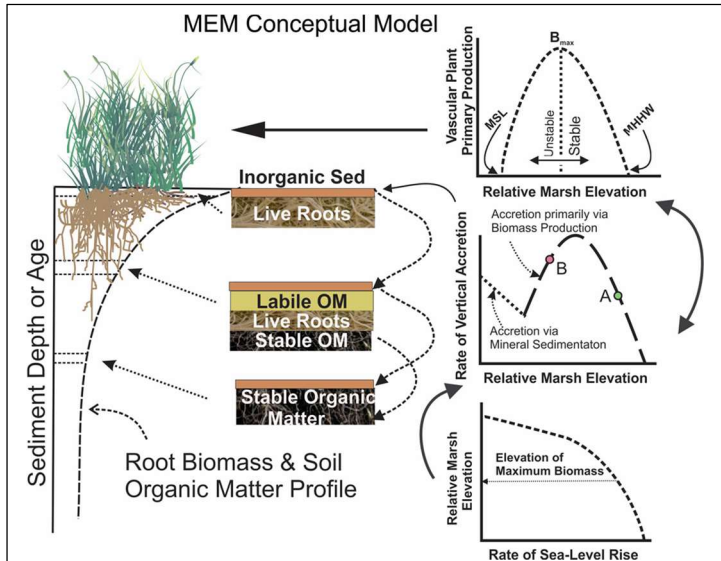


Fig. 11. Conceptual diagram of the Marsh Equilibrium Model (MEM). MEM is dynamic and simulates the response of a marsh to rising sea level. The feasible growth range (top graph) spans a vertical dimension approximately between mean sea level (MSL) and mean higher high water (MHHW). Growth declines to zero at the extremes due to stress from hypoxia at the low end and osmotic stress at the high end. Elevations greater than the optimum (the elevation of  $B_{max}$ ) are stable, e.g. the point A. Suboptimal elevations, e.g. point B middle graph, are unstable. At point B a rise in sea level (when relative elevation decreases) will decrease biomass production and decrease vertical accretion. On the super-optimal side (point A), when sea level rises, production and vertical accretion both increase. The equilibrium elevation will depend on the rate of sea-level rise as shown in the bottom graph. At super-optimal elevations, the equilibrium will decrease slowly as the rate of SLR increases, because rising biomass compensates by raising the accretion rate. At suboptimal elevations the decrease in relative elevation is rapid.

12 & 13). A surprising result is that fertilization had no effect on elevation gain. This differs from results at North Inlet where *fertilization has greatly increased* vertical accretion. PIE marshes have higher organic matter concentrations, and it is possible that added nutrients have increased decay rates in PIE plots, offsetting the expected gains in belowground production.

The model also makes the prediction that anomalies in mean sea level should affect marsh net primary production (NPP). Sea level can vary interannually by 10-30 cm during the summer growing season owing largely to variation in the

MEM is now coupled to a 2D version of the ADvanced CIRCulation (ADCIRC) model and computes spatial changes in marsh platform elevation across estuarine landscapes. An ADCIRC output, tide range, is a key input to MEM, and it varies spatially across the estuarine landscape. This affects the response of the marsh to rising sea level which, in turn, changes the hydrodynamics, and hence the distribution of tidal datums. The models predict that a 1 m rise in sea level this century will decrease the relative elevation of the marsh platform. The vegetated marsh will survive, but with replacement of the high marsh *S. patens* community by the low marsh *S. alterniflora* community. Our long-term observations support this pattern.

We are now testing additional model predictions including; 1) vertical accretion at lower elevations on the superoptimal side of the growth curve (Fig. 11) will be greater than at higher elevations, and 2) the concentration of soil organic matter will be greater at higher than lower elevations. Prediction 2 follows from the fact that sediment delivery to a site is proportional to the frequency and depth of flooding. Observations made at our long-term study sites support both predictions (Fig.

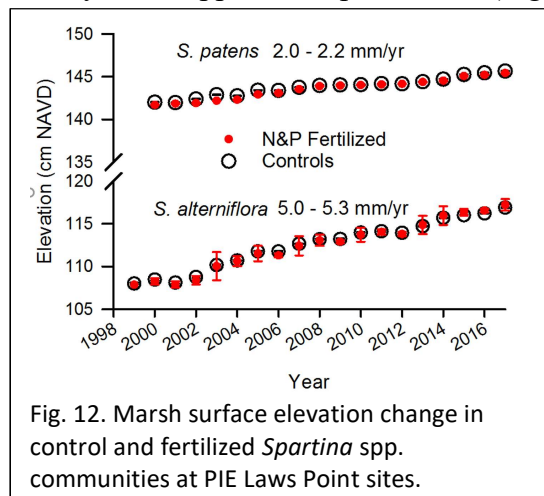


Fig. 12. Marsh surface elevation change in control and fertilized *Spartina* spp. communities at PIE Laws Point sites.

solar annual sea-level cycle. This cycle is a result of the seasonal thermal expansion of the ocean by as much as 30 cm, but there is quite a bit of variability in the timing of its peak and amplitude. NPP at PIE is less sensitive than at some other estuaries because of PIE's large tide range, but the effect can be seen in the long-term NPP data. At the *S. alterniflora* site there is a tendency for higher NPP when summer sea level is greater, as predicted. According to MEM, the elevation of this site is superoptimal for growth of *S. alterniflora*, so a rise in mean sea level should increase production (Fig. 14). On the other hand, the elevation of *S. patens* site is on the suboptimal side of its growth curve, so an increase in sea level should decrease production here (Fig. 14). Of course, other factors influence growth such as rainfall (see H2.1).

Much effort has been made to fully define the growth curves and optimal growth ranges of *Spartina* spp at PIE using multiple approaches described above. We have deployed marsh organs at PIE, as well as at 7 other locations on the east and Gulf coasts. Others have deployed marsh organs in many other locations including China. A generality has emerged that *S. alterniflora* has a vertical range that spans from approximately 10 cm below mean sea level to 30 cm above mean high water. The tide range at PIE (2.6 m) is too great to measure the full range of response in a marsh organ, but our field surveys and study of marsh bergs have allowed us to complete the curve.

Next Steps - Vertical accretion of the sediment surface is a function of mineral sediment and organic matter inputs, and decomposition (discounting deep compaction). At steady state, only the decay, or lack thereof, of the refractory part of organic matter is important. We are investigating this using wooden birch (high lignin content) dowels placed vertically in the

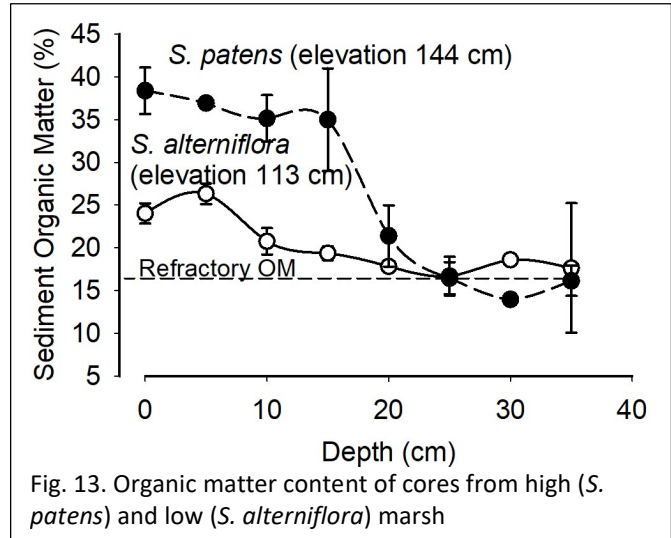


Fig. 13. Organic matter content of cores from high (*S. patens*) and low (*S. alterniflora*) marsh

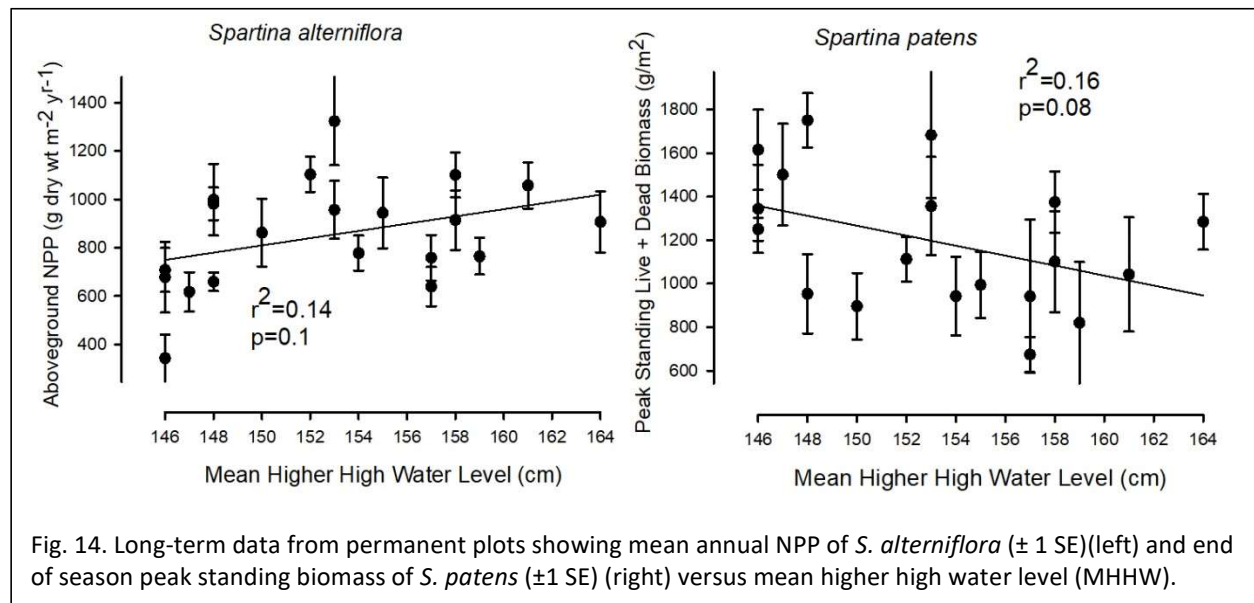


Fig. 14. Long-term data from permanent plots showing mean annual NPP of *S. alterniflora* ( $\pm 1$  SE)(left) and end of season peak standing biomass of *S. patens* ( $\pm 1$  SE) (right) versus mean higher high water level (MHHW).

sediment. They are deployed in the control and fertilized *Spartina* spp and *Typha* communities at PIE, in control and fertilized sites at North Inlet, and by collaborators in other estuaries, including Florida mangroves. The result will be a multivariate test of factors affecting the decay of a refractory material.

Rising sea level is affecting the distribution of salt water along the axis of the estuary. The impact on the saline marsh is quite modest but our data suggest the oligohaline marshes at the upper end of the estuary will be “squeezed”. This is beginning to happen at the *Typha* site where pore water salinity is tracking rising sea levels. We are now modeling soil salinity to predict the fate of the *Typha* zone with SLR.

**Q2) How will changing climate, watershed inputs, and marsh geomorphology interact to alter marsh and estuarine primary production, organic matter storage, and nutrient cycling?**

*H 2.1) Marsh primary production rates will increase as we transition from high marsh to more frequently flooded low marsh but net marsh C storage will not increase due to an overall loss in marsh area.*

In addition to the measurements of production outlined in H1.3, we measure vertical carbon exchange with continuous eddy covariance tower measurements in both high- and low-elevation marsh sites that allow us to assess overall marsh ecosystem metabolism and carbon cycling (Fig. 5). Six years of eddy covariance measurements in the high-elevation marsh and two years of measurements in the low-elevation marsh (only during the growing season due to ice) show interannual differences in marsh production are controlled, in part, by rainfall through changes in soil salinity. The annual net ecosystem exchange (NEE) in the high-elevation *S. patens* marsh averaged  $-180 \text{ g C m}^{-2} \text{ yr}^{-1}$  (2013-2017). Surprisingly, during the May to October growing season, NEE was not significantly different at the two sites: the low-elevation *S. alterniflora* marsh averaged  $-209 \text{ g C m}^{-2}$  and the high marsh averaged  $-238 \text{ g C m}^{-2}$ . However, we do see slight variation in the seasonality of the net uptake with the low marsh initializing growth and senescence earlier than the high marsh.

We measured the vertical exchange of carbon within specific ecosystem components using chambers on the vegetated marsh (transects comparing creek-bank and marsh interior with various plant types) in 2017 and in the aquatic (tidal creeks, ditches, and ponds) portions of the

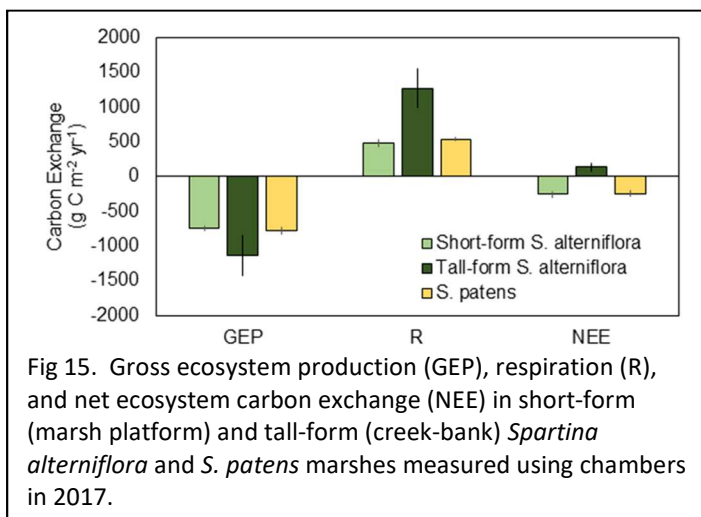


Fig 15. Gross ecosystem production (GEP), respiration (R), and net ecosystem carbon exchange (NEE) in short-form (marsh platform) and tall-form (creek-bank) *Spartina alterniflora* and *S. patens* marshes measured using chambers in 2017.

ecosystem from 2016-2019. Despite high rates of gross production, the tall-form creek-bank *S. alterniflora* areas do not appear to be sequestering carbon because of high respiration, resulting in a small net carbon loss from creek-bank marsh areas ( $136 \text{ g C m}^{-2} \text{ yr}^{-1}$ ; Fig. 15). The marsh platform in both the high- and low-elevation marsh exhibited similar rates of carbon sequestration in 2017 ( $-246$  and  $-261 \text{ g C m}^{-2} \text{ yr}^{-1}$ , respectively, Fig. 15). The annual rates of NEE from the eddy covariance towers can be compared to the NEE

derived from chamber measurements taken within the tower footprints (Fig. 16). The plot-level and eddy covariance tower measurements generally agree at both sites, lending confidence in our ability to measure carbon dynamics at both the ecosystem scale over multiple years (EC tower) and to elucidate specific habitat contributions to ecosystem carbon dynamics through measurements at the plot level (chambers). These measurements, however, also suggest that the rate of ecosystem NEE is quite similar between the high- and low-elevation marsh types at these two sites, indicating that our conversion to low-elevation *S. alterniflora* marshes may not increase production as we had hypothesized.

Although very close, the plot level measurements were 5-10% higher than the tower measurements (Fig. 16), which we suspect was due to efflux from the aquatic portion of the ecosystem offsetting marsh uptake, which would not be captured by the marsh chambers. To better constrain the aquatic flux of C, we utilized floating chambers to characterize the vertical air-sea exchange of CO<sub>2</sub> in tidal creeks, smaller ditches and headwater creeks, and isolated marsh ponds.

Larger tidal creeks and smaller headwater tidal creeks and mosquito ditches were consistent sources of C to the atmosphere (Fig. 17), indicating strong heterotrophy via marsh export of organic carbon and/or marsh export of dissolved inorganic carbon (DIC) into the estuarine water-column. Ponds which were not flushed on every tide were more variable and were both sources and sinks of carbon depending on the site and date (Fig. 17). Rates of CO<sub>2</sub> exchange appeared to be most strongly linked to the tide range on the date of sampling, which indicates that higher velocity water flows during higher tide ranges created more turbulence that facilitated gas exchange.

When we scale the measurements of aquatic efflux and marsh uptake (Fig. 17) to the relative area of each ecosystem component, we estimate that CO<sub>2</sub> evasion from the aquatic portion of the marsh system offsets approximately 6.5% of the marsh net ecosystem uptake of carbon, and can account for the differences between the chamber estimates of marsh production and tower estimates of whole-system carbon exchange (Fig. 16).

Next steps - We will continue to measure lateral exchanges of carbon to fully quantify the

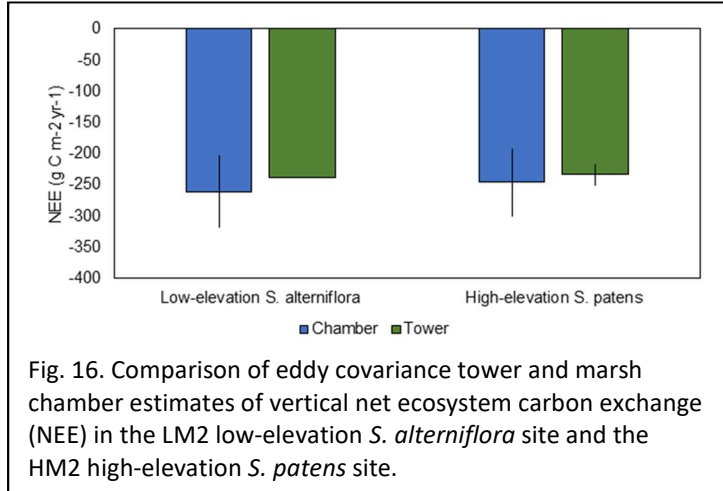


Fig. 16. Comparison of eddy covariance tower and marsh chamber estimates of vertical net ecosystem carbon exchange (NEE) in the LM2 low-elevation *S. alterniflora* site and the HM2 high-elevation *S. patens* site.

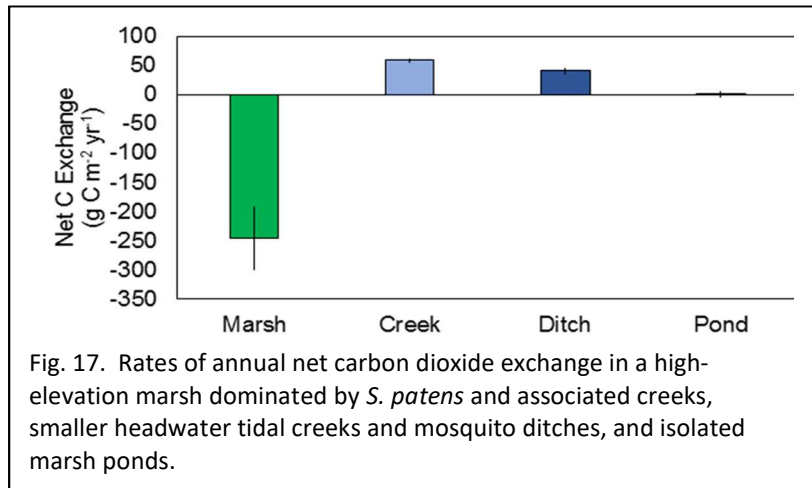


Fig. 17. Rates of annual net carbon dioxide exchange in a high-elevation marsh dominated by *S. patens* and associated creeks, smaller headwater tidal creeks and mosquito ditches, and isolated marsh ponds.

lateral exchange of C in these systems. In addition, we are analyzing longer-term (~100 yr) rates of C sequestration using Pb-210 dating techniques on marsh cores taken in both high and low marsh regions to look at historical changes to C sequestration.

**H2.2) Changes in climate, land use, and management in the watershed will increase freshwater flow, the amount of N delivered to the estuary, and the variability of the estuarine salinity and nutrient regime.**

The same factors that influence TSS fluxes to the estuary – climate, land use, and water management - also affect water and nitrogen fluxes, two other critical controls of estuarine processes. Historical reconstruction of the water budget indicates that although precipitation has increased since 1934 by about 20% (Claessens et al. 2006), evapotranspiration and net human water withdrawals (interbasin water transfers) have offset much of this increase, resulting in little net change in discharge to the estuary. Since 2008, net water withdrawals have started to decline (Wollheim et al. 2013), but recent decreases in precipitation have overwhelmed any change in observed runoff that may have resulted. Our previous work has shown that N retention by the PIE watersheds is higher than for other northeastern watersheds (Wollheim et al. 2013) and climate variability is a predominant control of N fluxes to the estuary, with little evidence of changes due to suburbanization since 1994 (Morse and Wollheim 2014). We hypothesize aquatic N retention is increasing due to a greater abundance of beaver ponds since 1999 that has acted to counter any increased loading due to land use change. As a result, we have in recent

years focused efforts on understanding the N retention capacity of fluvial wetlands, beaver ponds (Wollheim et al. 2014, Whitney 2017) and anthropogenic reservoirs.

A quantitative conceptual model, the River Network Saturation (RNS) Concept (Wollheim et al. 2018), was recently proposed to describe the role of river networks in regulating material fluxes across flow conditions. The RNS Concept mathematically demonstrates the tendency for river networks to become saturated (supply > demand) under higher flow conditions when delivery of materials increases faster than sink processes can respond. (Fig. 18). However, the flow thresholds under which saturation occurs depends on a variety of factors, including the inherent process rate for a given constituent and the abundance of lentic waters such as lakes, ponds, reservoirs, and fluvial wetlands, that enhance demand for some constituents, like nutrients, within the river network. The model has been implemented specifically in the Ipswich River watershed within FrAMES to test scenarios of N

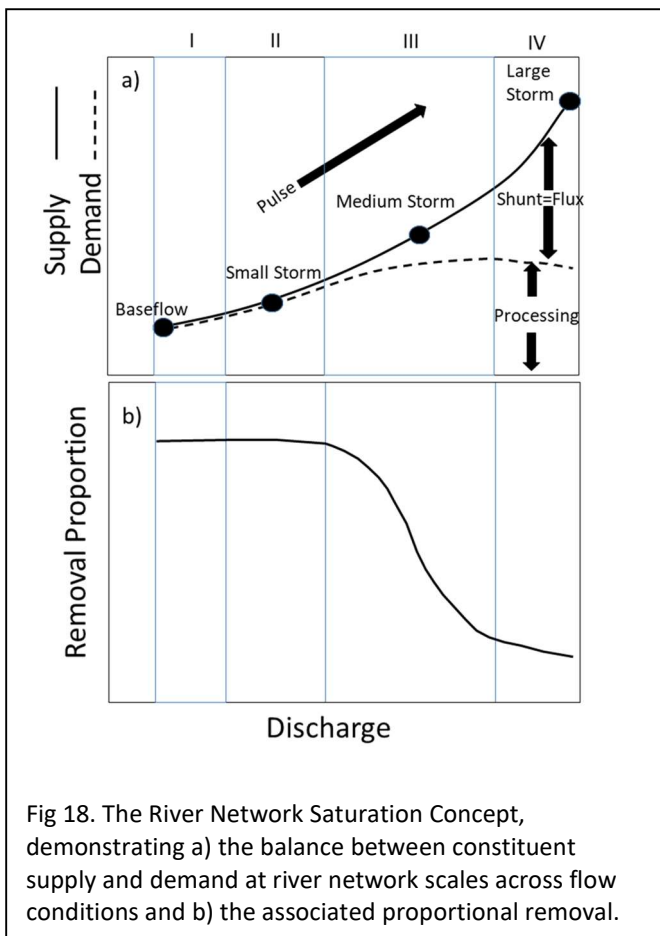


Fig 18. The River Network Saturation Concept, demonstrating a) the balance between constituent supply and demand at river network scales across flow conditions and b) the associated proportional removal.

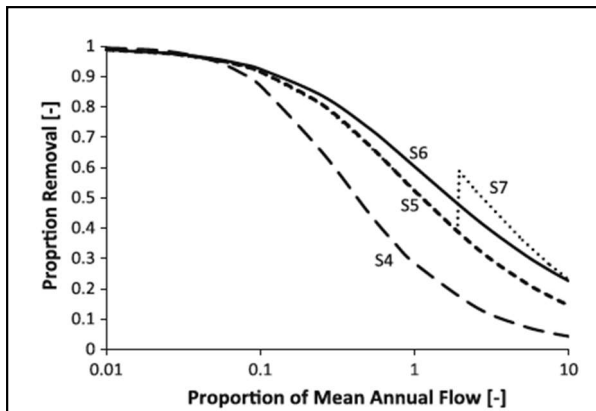


Fig. 19. Model relationship between river network scale proportion removal and flow conditions for the Ipswich R. watershed. S4 assumes a channelized river network only, S5 adds lakes and reservoirs, S6 includes beaver ponds with density =  $0.8 \text{ km}^{-1}$  of river length and S7 assumes flood plains become active at 2x the mean annual flow. The model demonstrates the dynamics hypothesized by the River Network Saturation Concept.

retention by the river network assuming channels only, then sequentially adding lakes and reservoirs, beaver ponds, and flood plains (Fig. 19). The RNS concept is informing our measurements such as our emphasis on the factors regulating supply (storm event response) and demand for different nutrients in different types of water bodies (beaver ponds, reservoirs).

In addition to continuation of the long-term monitoring, watershed research under the current LTER proposal focuses on the factors influencing nitrogen demand within the river system. We have conducted nitrate solute additions to beaver ponds (Whitney 2017) and have quantified the complete N mass balance of one anthropogenic reservoir and one beaver pond. We have also compared N retention across 7 additional reservoirs in the Ipswich and Parker R. watersheds, and in neighboring coastal New Hampshire. The long-term goal is to determine how a shift from anthropogenic

reservoirs located mainly downstream to beaver ponds located mainly in the headwaters will affect N exported to the estuary.

The comprehensive N budget of the South Middleton reservoir revealed that this small reservoir is a strong DIN sink, but is a source of DON and PON (Figure 20). The production of DON and PON (as algal production) offset roughly  $\sim 50\%$  of DIN retention. Most of the net DIN retention and DON production occurs during spring, when supply of DIN to the reservoir is high, temperatures are starting to warm, and solar radiation is relatively high, suggesting a “hot moment” of internal N cycling in the reservoir. Similar results were found across a wide range of coastal New England reservoirs, with smaller reservoirs having higher DIN removal proportions, with some of the DIN transformed to DON.

Tradeoffs between N removal and greenhouse gas ( $\text{CO}_2$ ,  $\text{CH}_4$ , and  $\text{N}_2\text{O}$ ) production are also an important consideration in both anthropogenic reservoirs and beaver ponds. The PIE watersheds are characterized by a large proportion of suburban land ( $\sim 35\%$ ) with high N loading and high wetland abundance ( $\sim 20\%$ ) (Wollheim et al. 2016), so these watersheds may be hotspots of  $\text{N}_2\text{O}$  production. The impacts of urbanization on GHG production in surface waters has not yet been evaluated by the research community. LTER PhD student Andrew Robison has begun to quantify freshwater GHG evasion in the PIE watersheds,

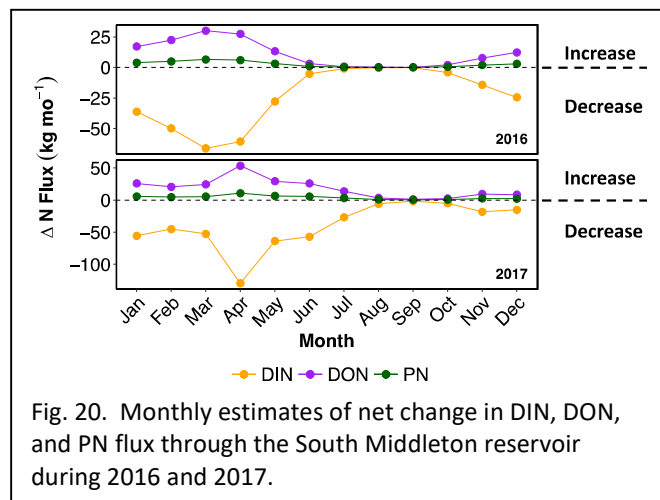


Fig. 20. Monthly estimates of net change in DIN, DON, and PN flux through the South Middleton reservoir during 2016 and 2017.

focusing on the impacts of land use on  $p\text{CO}_2$  fluxes in urban vs. forested streams, using newly developed, high frequency sensors, as well as  $\text{CH}_4$  and  $\text{N}_2\text{O}$  flux measurements. Preliminary results show that flux of  $\text{CO}_2$  emissions increase considerably during storms even in a flashy urban stream, suggesting a) urban streams can be major GHG sources despite less terrestrial vegetation and b) that much of this evasion occurs during storms.

Next Steps PhD student Whitney and UNH Masters student Sarah Bower are currently quantifying GHG concentrations along fluvial wetland transects, larger rivers, beaver ponds, and reservoirs. The combination of all these measurements will ultimately allow us to evaluate the relative importance of each of these water bodies within an entire river network, and how this might change under different climate regimes, land use, and predominant type of surface water (channelized, beaver ponds, reservoir).

**H2.3) Coupling between the marsh and the estuarine water column will increase, fueling more estuarine production and respiration, increased net heterotrophy, and accelerated N cycling.**

The relatively high  $\text{CO}_2$  emissions from the tidal creeks (Fig. 17) would suggest that lateral (tidal) dissolved inorganic carbon (DIC) export could be an important component of system carbon dynamics and lead to an underestimate of total C loss by atmospheric measurements alone. To address this, and to examine losses of dissolved nutrients and organic matter, we have undertaken significant effort to understand the lateral, tidal exchange of carbon, nutrients, and sediment between the marsh system and estuarine waters, and how this exchange differs between high- and low-elevation marsh areas. To assess lateral exchange, we conduct 12 hour import/export measurements in tidal creeks that drain either predominately high-elevation or low-elevation marsh creeksheds during which the net exchange of water, carbon, sediments, and nutrients is measured every 15 minutes. Lateral exchange is assessed three times per year (spring, summer, and fall); we have conducted over 50 of these measurements during this funding period. There are clear differences in DIC, TSS, and nutrient concentrations between high and low tide, and there are notable differences in material exchange between the marsh types for some parameters. Surprisingly, though, there is little net exchange of DIC regardless of

marsh type. In contrast, results for total suspended sediment (TSS) exchange show that ebb tides are depleted in sediment relative to flood tides, indicating the marsh sites are importing and retaining sediments (Fig. 21). The low-elevation *S. alterniflora* marsh systems retain more sediment on average ( $3.1 \pm 0.9 \text{ g m}^{-2} \text{ tide}^{-1}$ ) than high-elevation *S. patens* marshes ( $0.70 \pm 0.40 \text{ g m}^{-2} \text{ tide}^{-1}$ ), which is likely linked to the greater duration and depth of

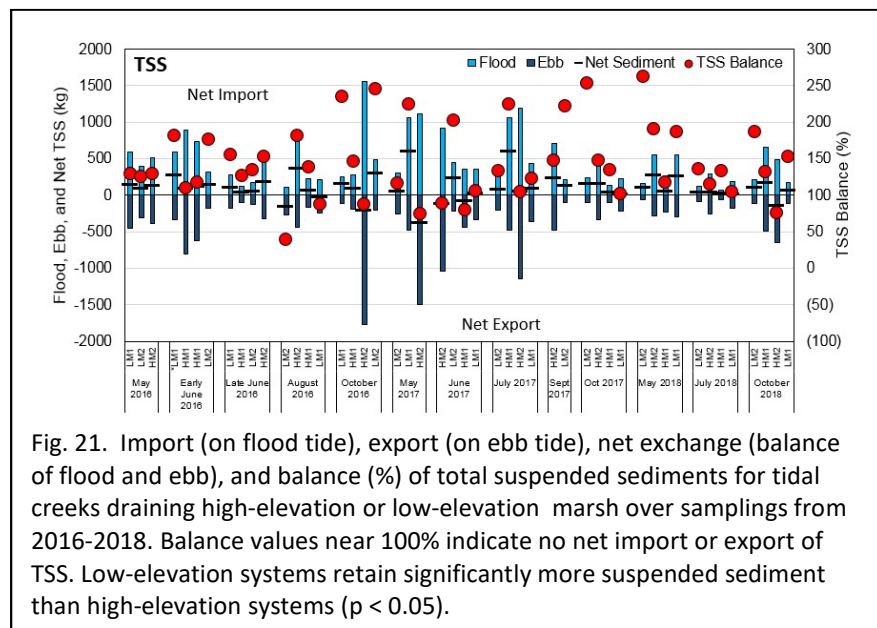


Fig. 21. Import (on flood tide), export (on ebb tide), net exchange (balance of flood and ebb), and balance (%) of total suspended sediments for tidal creeks draining high-elevation or low-elevation marsh over samplings from 2016-2018. Balance values near 100% indicate no net import or export of TSS. Low-elevation systems retain significantly more suspended sediment than high-elevation systems ( $p < 0.05$ ).



flooding in the low-elevation marshes. When extrapolated to a full year, sediment retention in the low-elevation marshes contributes significantly to marsh accretion ( $0.72 \text{ mm yr}^{-1}$ ), but has a very limited contribution to vertical accretion in the high-elevation marsh ( $0.16 \text{ mm yr}^{-1}$ ).

Biogeochemical cycling differs between high- and low-elevation marshes in other ways. For instance, low-elevation *S. alterniflora* marshes retained more nitrate ( $\text{NO}_3^-$ ) than high-elevation marshes. We suspect that the greater duration of flooding in low-elevation marshes provides more opportunity for plant uptake and denitrification that removes  $\text{NO}_3^-$  from flood water.

We further explore the coupling between the marsh and estuary by measuring aquatic production and respiration in estuarine water draining these same high- and low-elevation marsh creeksheds and throughout the estuarine system. We have measured water-column production and respiration rates at six “transition” sites on water collected on ebb tide shortly after high tide. Primary production in the high marsh systems was significantly higher than in low marsh systems, likely reflecting greater nutrient removal from estuarine water in contact with low-elevation marshes.

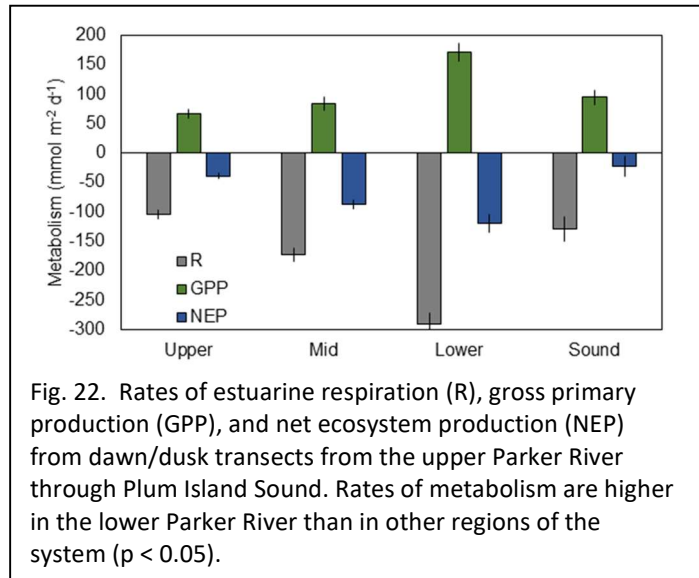


Fig. 22. Rates of estuarine respiration (R), gross primary production (GPP), and net ecosystem production (NEP) from dawn/dusk transects from the upper Parker River through Plum Island Sound. Rates of metabolism are higher in the lower Parker River than in other regions of the system ( $p < 0.05$ ).

Whole estuarine ecosystem metabolism has been measured during spring, summer, and fall along transects from the mouth of Plum Island Sound system up the Parker and Rowley Rivers at dawn and at dusk to capture changes in dissolved  $\text{O}_2$  and DIC during 2.5 day/night periods. These data, when corrected for air-sea exchange and dispersion, yield measurements of estuarine metabolism (Fig. 22). Areal rates of metabolism tend to be highest in the lower portion of the Parker River, with all regions of the estuary system demonstrating net heterotrophy (Fig. 22).

Next Steps We will update previous analyses of whole-ecosystem metabolism based on dawn/dusk transects to complete an assessment of 20+ years of these transects to evaluate long-term changes in metabolism in the Plum Island system in response to land use change, climate change, or other long-term shifts in the ecosystem.

### Q3) How will key consumer dynamics and estuarine food webs be reshaped by changing environmental drivers, marsh-estuarine geomorphology and biogeochemistry?

**H3.1)** *Sea level rise will shift estuarine food webs toward dominance by marsh-marine food webs due to shifts in habitat configuration and productivity, with cascading consequences for trophic dynamics.*

Sea level rise in the context of marshes will similarly affect biological communities via multiple mechanisms. At PIE, we have identified 1) marsh “squeeze”, – compression of marshes and loss when there is nowhere for them to migrate, and 2) “transition”, increases in the dominance of low marsh vegetation, as two of the likely mechanisms which will most dramatically affect salt marsh biotic community structure and ecosystem function. These changes

tie directly into ecological theory, giving us an opportunity to test how well theory enables us to forecast changes due to sea level rise.

Theory predicts that shifts in landscape features should reshape food web structure (species present) and their interaction strengths, with cascading consequences for ecosystem structure and function (Chase and Knight 2013, Keil et al. 2015, Rocha et al. 2015). This prediction is rooted in the theory of Biodiversity Ecosystem Function (BEF; Loreau 1996, Tilman et al. 1999, O'Connor and Byrnes 2013) – that changes in biodiversity could influence changes in productivity and other ecosystem functions due to consequences arising from coexistence mechanisms. However, as BEF has developed, we have recognized 1) that non-random species loss can affect the shape of the BEF relationship (Bracken and Williams 2013), 2) that different species can affect different functions, leading to a need to consider the simultaneous performance of multiple functions, or so-called multifunctionality (Gamfeldt et al. 2008, Byrnes et al. 2014), and 3) that ultimately biodiversity is but one metric of community structure that can affect ecosystem function. Salt marshes have been one place where researchers have explicitly made the leap to looking at the link between community structure and multiple ecosystem functions (Angelini et al. 2015), thus showing how the framework of BEF might be used to establish a more concrete link between Community Ecology and Ecosystem Ecology. At the PIE LTER, we have attempted to use this theoretical framework (Fig. 23) to examine how marsh squeeze and low marsh transition influence community structure, and whether these two aspects of SLR rise influence salt marsh ecosystem function directly or indirectly via changes in community structure.

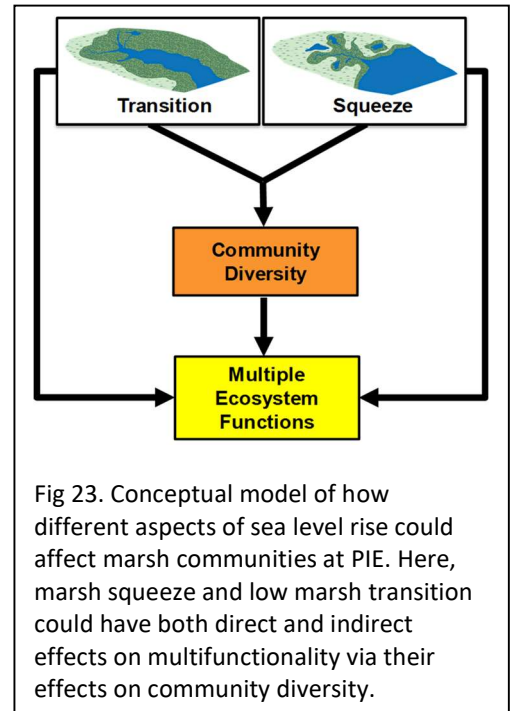


Fig 23. Conceptual model of how different aspects of sea level rise could affect marsh communities at PIE. Here, marsh squeeze and low marsh transition could have both direct and indirect effects on multifunctionality via their effects on community diversity.

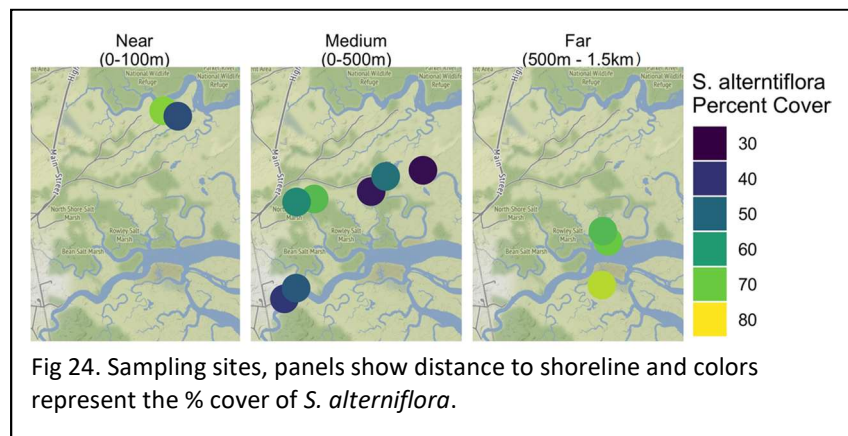


Fig 24. Sampling sites, panels show distance to shoreline and colors represent the % cover of *S. alterniflora*.

In 2017 and 2018 we sampled marsh sites that varied in site properties in a space-for-time approach that aligns with our conceptual model. Marshes were chosen to be either near to or far from an upland border as an analogue for marsh squeeze. Marshes were also chosen to vary in site-level cover of *Spartina alterniflora*, with higher cover representing

marshes that had undergone SLR. Our sites (Fig. 24) varied in both properties, and included sites close to the upland border having both low and high cover of *S. alterniflora*, a wide variety of intermediate sites for which both properties were largely crossed, and a few sites that were both far from the upland and had high *S. alterniflora* cover. At these sites we measured a wide suite of

community properties – vegetation cover, mobile invertebrate abundance, fish abundance, bird abundance, and terrestrial invertebrate abundance. We also measured total standing biomass, predation rates, herbivory rates, sedimentation rates, and decomposition rates as measures of ecosystem function.

Broadly, we found individual aspects of community structure of ecosystem function were correlated with either distance from upland, *S. alterniflora* cover, both, or their interaction. For example, green crab abundances were highest in marshes furthest from the upland (Figure 25). While we are still sorting terrestrial invertebrate samples, putting the currently exiting data together using Structural Equation Modeling (Grace 2006), we begin to find some support for our conceptual model. For example, in a model looking at effective diversity (Jost 2006) of birds, plants, pitfall trap invertebrates, and creek mobile organisms as metrics of community structure and at a single metric of multifunctionality (average function multiplied by functional evenness), we find that our proxies for SLR effects affect marsh multifunctionality solely via changes in plant community diversity (Fig. 26). Further, this model shows that multifunctionality is coupled to multiple aspects of community structure – although not all.

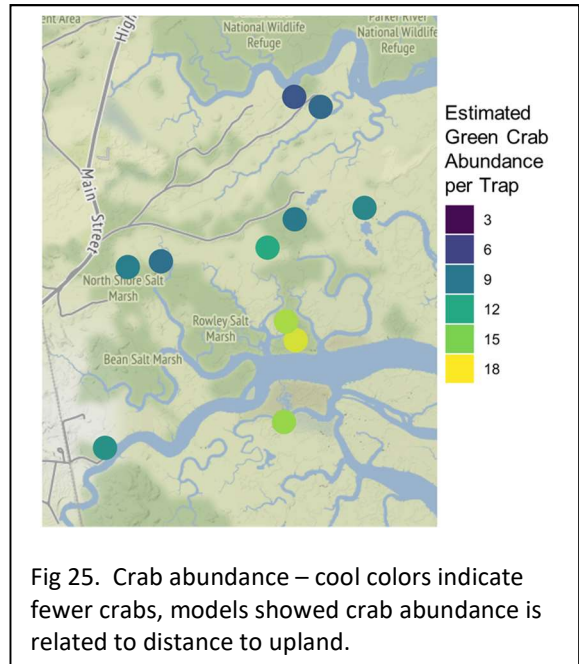


Fig 25. Crab abundance – cool colors indicate fewer crabs, models showed crab abundance is related to distance to upland.

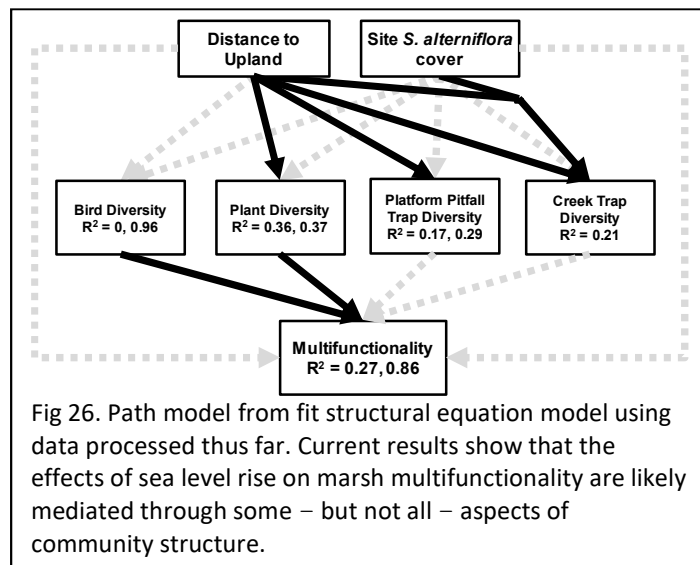
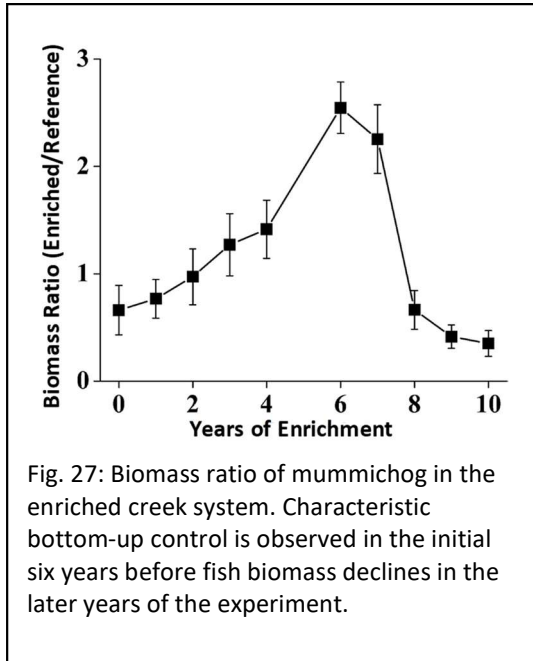


Fig 26. Path model from fit structural equation model using data processed thus far. Current results show that the effects of sea level rise on marsh multifunctionality are likely mediated through some – but not all – aspects of community structure.

Our preliminary results suggest that the conceptual framework of SLR affecting community structure which then affects multiple ecosystem functions is likely correct. Moreover, our work begins to advance the exploration of linking community structure and ecosystem function. With the terrestrial invertebrate samples being finished in 2019, we're confident that this work will have broad relevance for both conceptual and applied ecology.

Additional insights into impacts of geomorphic change came from an unexpected direction, a nutrient enrichment experiment. Classic bottom-up theory predicts that increased

resource availability (e.g., nutrients) at the base of the food web will stimulate primary production and, in turn, secondary production (Menge et al., 2003; Ware and Thomson, 2005; Spivak et al., 2007). Recent studies, however, indicate that bottom-up controls on food web production may be modified by other factors, such as landscape configuration and continuity. As part of a 10-year, ecosystem-scale experiment in a New England salt marsh we investigated the

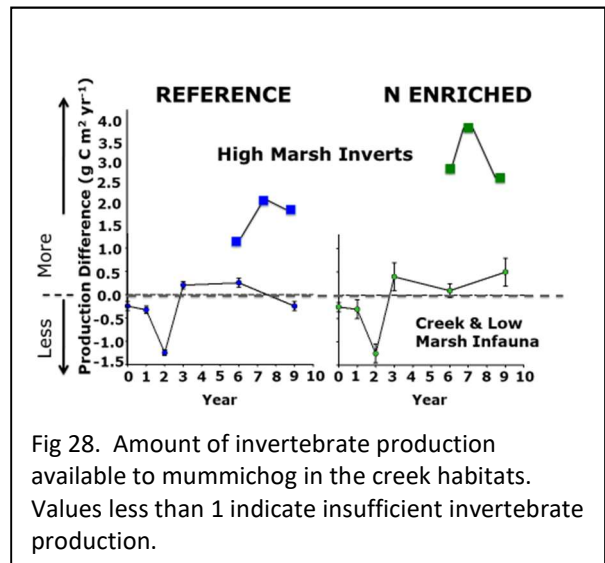


response of secondary consumers, specifically a fish mummichog (*Fundulus heteroclitus*), to nutrient enrichment (Nelson et al. 2019). In the first six years, we observed a classic bottom-up response of increased mummichog production. However, after the 6<sup>th</sup> year, mummichog biomass and abundance declined despite continued bottom-up stimulation of the food web (Fig. 27).

To determine the mechanism for the decline in mummichog biomass we evaluated the total production of invertebrate prey available to mummichog in the creek mudflats, low marsh, and high marsh habitat. Mummichog can access mudflat and low marsh habitats twice daily with the rising tides, while the high marsh habitat is only accessible a few hours each month during the spring tides. Based upon annual biomasses, mummichogs would require all, or nearly all, of the invertebrate biomass in both the enriched and reference creek systems

(Johnson and Fleeger 2009, Nelson et al. 2019). However, when high marsh invertebrate production was included accessing the high marsh would provide sufficient prey to sustain the mummichog biomass typically observed (Fig. 28). To determine how critical access to this high marsh prey was, we conducted controlled feeding experiments. Mummichog are omnivorous and known to consume significant amounts of detritus and plant material, as well as invertebrate prey, but it was unclear how the relative amount of food items altered mummichog growth and condition (Lockfield et al. 2013). We determine that while mummichog are capable of surviving on a plant-based diet, access to protein is critical to their growth and condition (Fig. 29).

In the sixth year of the nutrient enrichment experiment the geomorphology of the creek edges began to change and decoupled high and low marsh habitats (Deegan et al. 2012). Our experiments and observations indicated that this geomorphic change was likely responsible for the decreased mummichog biomass (Fig. 27). We tested our hypothesis outside of the nutrient enrichment at three creeks along a geomorphic gradient and observed increasing mummichog abundance with increasing geomorphic connectivity, supporting our hypothesis that geomorphology was controlling mummichog biomass and overriding bottom-up stimulation in the nutrient enrichment experiment (Fig. 30). We conclude that the nutrient-induced spatial change in habitat structure altered the energy flow across landscape elements in the food web, and this effect was greater than the bottom-up stimulation in the habitats that were still



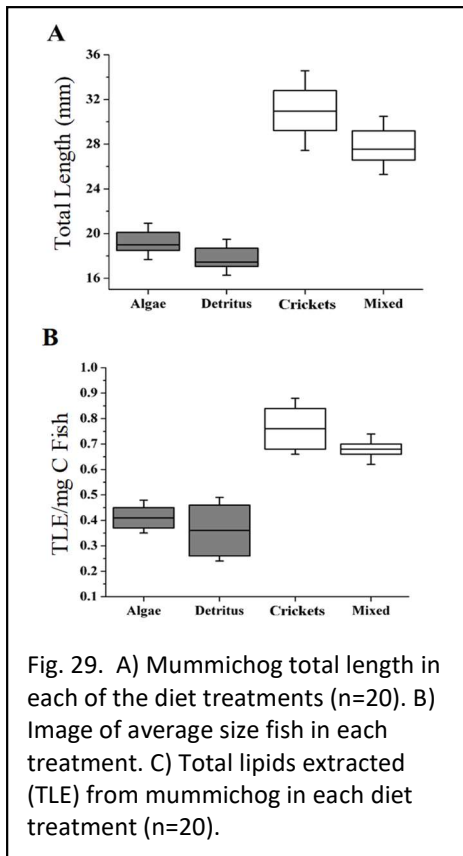


Fig. 29. A) Mummichog total length in each of the diet treatments (n=20). B) Image of average size fish in each treatment. C) Total lipids extracted (TLE) from mummichog in each diet treatment (n=20).

accessible. The functional loss of access to essential production sources via the change in creek habitat structure overrode the initial bottom-up stimulation of the food web and caused a decline in mummichog production.

Loss of habitat area and quality of creek edge marsh have ecosystem-scale impacts that are disproportionate to the areal extent of this habitat (4% of the vegetated marsh) because of their critical role in providing access to the much larger area of high marsh. Our results suggest that nutrient enrichment and landscape configuration are competing controls on secondary production and that identifying which mechanism is operating in a system is important to understand how a system may respond to change. These results provide insight into the function of spatially coupled food webs. Higher trophic level organisms utilize and connect multiple food web channels via their movement (Neutel et al. 2007, Rooney et al. 2008). Others have observed, and we provide further

evidence here, that food webs become increasingly coupled at higher trophic

levels (Rooney et al. 2008, McCann 2012). In our system, the more compartmentalized saltmarsh creek and marsh platform food webs are coupled in space by mummichog. In turn mummichogs are a critical food web node that couples terrestrial (wading birds) and aquatic (fish) predator food webs (Fig. 31).

The expected general habitat transition in the PIE ecosystem from a *S. patens* dominated high marsh to a *S. alterniflora* low marsh habitat will alter

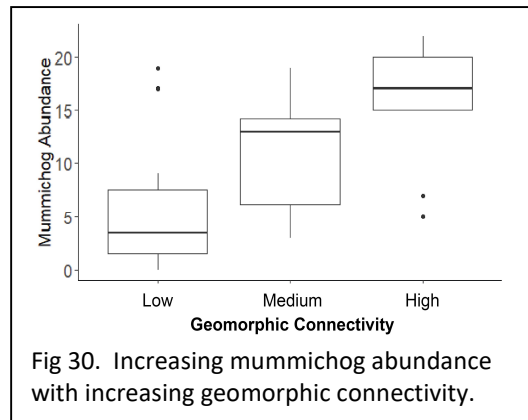


Fig 30. Increasing mummichog abundance with increasing geomorphic connectivity.

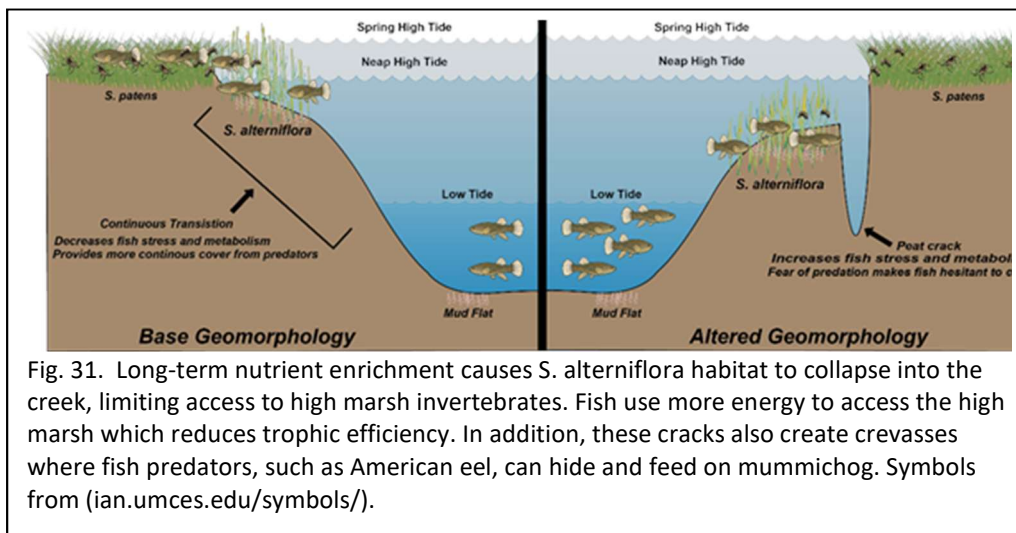


Fig. 31. Long-term nutrient enrichment causes *S. alterniflora* habitat to collapse into the creek, limiting access to high marsh invertebrates. Fish use more energy to access the high marsh which reduces trophic efficiency. In addition, these cracks also create crevasses where fish predators, such as American eel, can hide and feed on mummichog. Symbols from (ian.umces.edu/symbols/).

both the heterogeneity of habitat as well as the geomorphic structure. Although there is generally little theory on the effects of decreased habitat heterogeneity and altered

habitat structure on food webs *see* (McCann and Rooney 2009, Wimp et al. 2010) our results suggest that habitat loss will decrease food web complexity and connectivity (Montoya et al. 2006, Chase and Knight 2013, Keil et al. 2015).

Next Steps – We will continue to sample five of the space-for-time sites using the same protocols. This long-term community monitoring will allow us to evaluate our predictions, as well as develop a deeper understanding of how sea level rise will influence the marshes of the PIE LTER as the marsh transitions.

**H3.2) Food web and ecosystem function will be altered by range expansion into the estuary of more southern species, such as the fiddler crabs.**

The ocean boundary of the Plum Island Ecosystem LTER is the Gulf of Maine, which is warming faster than almost any other part of the world’s oceans (Pershing et al. 2015). Because of this warming, warmer-water species that formerly had a northern limit of Cape Cod, Massachusetts, are now expanding their ranges into the Gulf of Maine. This follows the general pattern seen worldwide where ocean and atmospheric warming lead to species expanding or shifting their range from lower to higher latitudes or altitudes (Pecl et al. 2017). We have documented two range expansions into the PIE-LTER: the blue crab, *Callinectes sapidus*, and the mud fiddler crab, *Uca pugnax* (Johnson 2014, Johnson 2015). The appearance of the fiddler crab, *Uca pugnax*, is significant because in marshes to the south, it is considered an important burrowing crab that impacts marsh grass productivity, pore water drainage, and provides an important food supply for birds.

Fiddler crabs were first discovered in the PIE marshes in 2014 (Johnson 2014). Since then, we have tracked their populations through annual burrow counts in 6 tidal creeks. From 2014 to 2018 their densities have more than tripled (Fig. 32). Despite this increase in population, the PIE population is small (up to 8 burrows m<sup>-2</sup>) relative to populations found south of Cape Cod where populations range from 80-150 burrows m<sup>-2</sup>. Fiddler crabs are spreading throughout the salt marshes at PIE. In 2014 we surveyed 21 marshes and found fiddler crabs in 75% of them. In 2018 we reconducted the survey and found fiddler crabs in 100% of the marshes. Because the fiddler crab population is persistent, growing, and spreading, it suggests that this climate migrant has successfully colonized PIE and is here to stay.

Because there is a clear distinction between the historic range (south of Cape Cod) and expanded range (north of Cape Cod), the range expansion of the fiddler crab presents an excellent natural experiment to test ecological hypotheses. One such hypothesis is the enemy-release hypothesis (Keene and Crawley 2002), which posits that when a species successfully colonizes a new range it does so, in part, because it has left some of its enemies behind. The enemy-release hypothesis has been tested extensively for invasive species, but rarely for climate migrants. We tested the specific hypothesis that fiddler crabs in the Gulf of Maine (expanded

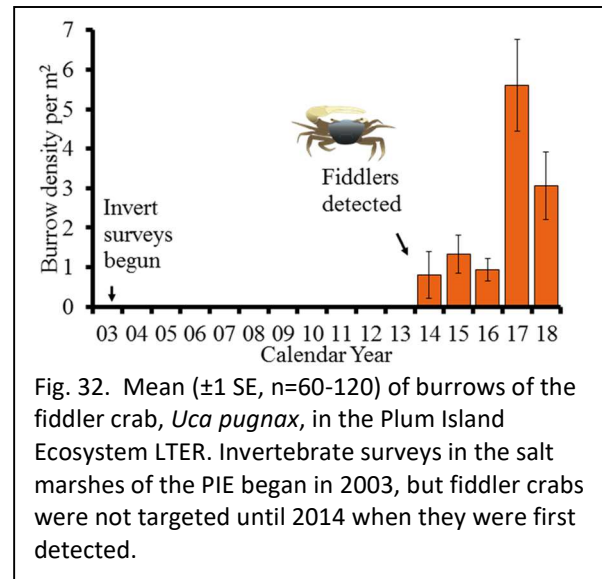


Fig. 32. Mean ( $\pm 1$  SE, n=60-120) of burrows of the fiddler crab, *Uca pugnax*, in the Plum Island Ecosystem LTER. Invertebrate surveys in the salt marshes of the PIE began in 2003, but fiddler crabs were not targeted until 2014 when they were first detected.

range) have escaped its parasites from the historic range. Based on a survey of ten marshes from Georgia to New Hampshire that included two other LTERs (VCR and GCE), we found that fiddler crabs in the historic range had 5x more parasite species than those in the expanded range (Fig. 33, Johnson et al. a, submitted), which supports the enemy-release hypothesis. Additionally, fiddler crabs in the Gulf of Maine have escaped competitors in the historic range, including the purple marsh crab, *Sesarma reticulatum*, the wharf crab, *Armases cinerium*, and the two other Atlantic fiddler crabs – *U. minax* and *U. pugnax*. Our work demonstrates that despite being adjacent to their enemy-filled historic range, climate migrants are able to escape some of their enemies when they expand or shift their ranges.

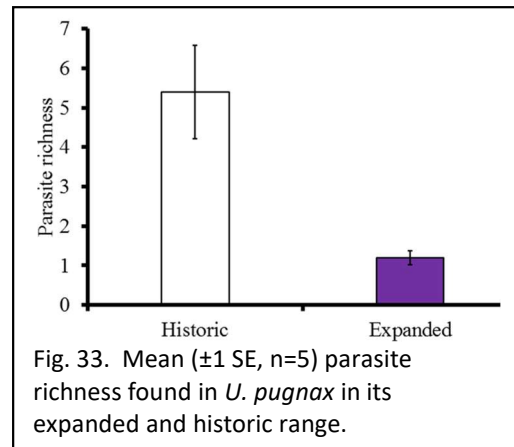


Fig. 33. Mean ( $\pm 1$  SE, n=5) parasite richness found in *U. pugnax* in its expanded and historic range.

Based on a latitudinal survey of *U. pugnax* from Florida to Massachusetts that included the VCR and GCE LTERs, we found that, on average, for every degree of latitude, the body size of male crabs increases by 0.5 mm (Johnson et al. b in review). When the body size of an organism increases from low to high latitudes, this is known as Bergmann's rule (Bergmann 1847), a well-known biogeographic pattern.

While we have documented thousands of climate migrants like *U. pugnax* across the planet (Pecl et al. 2017), we still know little about how these species will influence ecosystem functioning. Fiddler crabs are bioturbating ecosystem engineers whose burrowing and feeding can influence marsh function including aboveground and belowground plant biomass, sediment deposition, benthic algal biomass, benthic infauna composition and decomposition. Byrnes is addressing the question of density-dependent effects of fiddler crabs on marsh functioning. Those experiments have been conducted and the data are currently being generated.

Next Steps Johnson recently obtained an NSF grant to examine the effect of body-size on the magnitude of response of marshes to fiddler crabs. The hypothesis is that the bigger crabs in PIE will have larger per-capita impacts than the smaller crabs in GCE. This experiment will be conducted as a cross-LTER site (PIE, VCR, GCE) caging study in 2020.

**H3.3) Environmental changes will reshape community structure toward higher abundances of omnivorous species that increase food web stability and of mobile consumers that forage across habitat boundaries.**

Spatially coupled food webs and omnivory can stabilize food webs against top-down perturbations and respond contrary to top-down theory. Identifying these responses can be difficult as population level responses can be masked (Nelson et al. 2015, 2019). Responses to bottom-up perturbations may also be hard to recognize if organisms respond to changes in productivity on annual or longer temporal scales. To understand how these factors change food web dynamics and resource use we are applying recently developed niche metrics to our long-term monitoring data of stable isotope values of key consumers in the PIE food web. Results are providing a better understanding of how resource use varies with known drivers of productivity and how PIE food webs will respond to long-term change.

Initial analysis of our long-term isotope records against the long-term water quality and climatic data has identified general trends with niche size correlated with temperature. In years

with higher mean air temperature we see an overall decline in niche-size, indicating decreased variability in resource use and perhaps a greater focus on a preferred resource (Fig 34). However, the primary drivers for changes in niche size vary with species. For example, the softshell clam increases trophic level in years with higher temperatures, indicating this filter feeder is consuming higher trophic level prey and suggesting greater trophic efficiency in the water column.(Fig. 34). Mummichog, however, respond by decreasing their dependance on the detrital channel of the food web, relying less on saltmarsh detritus derived material (Fig. 34).

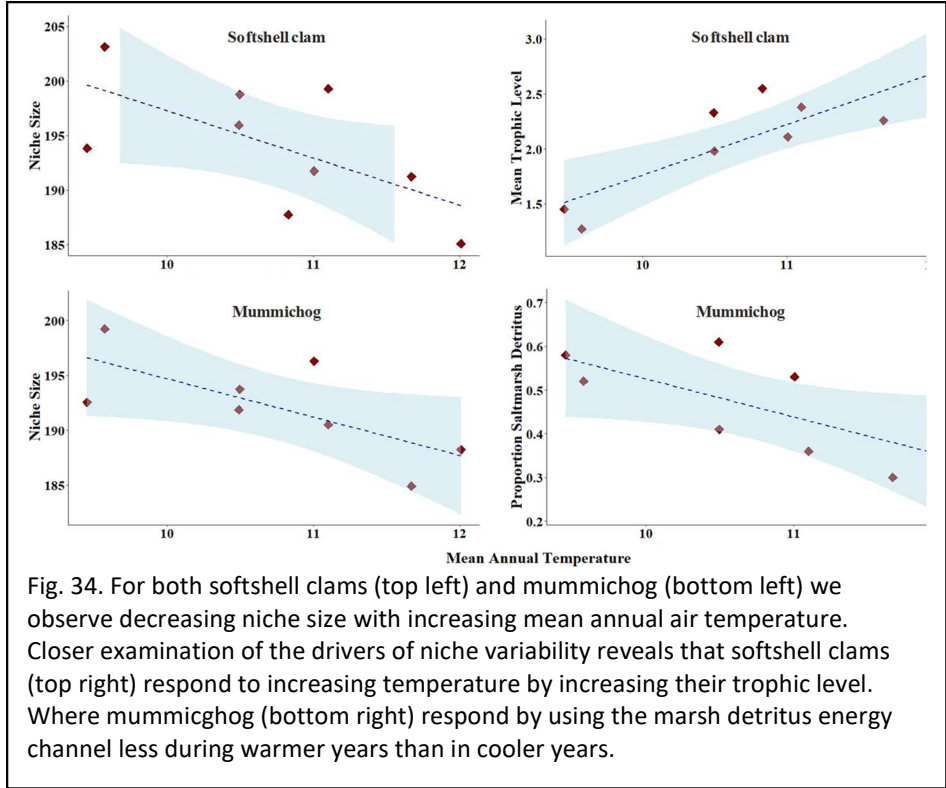


Fig. 34. For both softshell clams (top left) and mummichog (bottom left) we observe decreasing niche size with increasing mean annual air temperature. Closer examination of the drivers of niche variability reveals that softshell clams (top right) respond to increasing temperature by increasing their trophic level. Where mummichog (bottom right) respond by using the marsh detritus energy channel less during warmer years than in cooler years.

Next Steps – We are now modeling the full systems dynamics to address how the dynamics of marshes and higher trophic level organisms will change due to increasing temperatures and to range expansions.

#### IV. Highlights of New Directions:

##### Metagenomics assembled genomes that respond to nitrate enriched marsh sediment

In earlier work we collected sediments from the Plum Island LTER salt marsh and performed controlled experiments that allowed us to directly manipulate the quantity of nitrate available to marsh sediment microbes (Bulsecu et al. 2019). We showed that this added nitrate stimulated respiration by denitrification and dissimilatory nitrate reduction to ammonia (DNRA) and that there was a pool of organic matter that was accessible for decomposition by microbes in the presence of nitrate that was not decomposed when sulfate was the predominant electron accept present (Bulsecu et al. 2019). Short-read metagenomic analysis highlighted that genes for central carbon metabolism, denitrification, and DNRA were all enhanced in the nitrate added treatment (Bulsecu et al. In press). This short-read analysis suggested that genes for carbon fixation were also enhanced under high nitrate conditions, suggesting a role for chemoautotrophy in this system.

We are currently analyzing this same suite of samples from the Plum Island LTER to reconstruct metagenomics assembled genomes from this experiment. Of the recovered genomes, many were found ubiquitously in our samples and contain the genetic capacity for fermentation



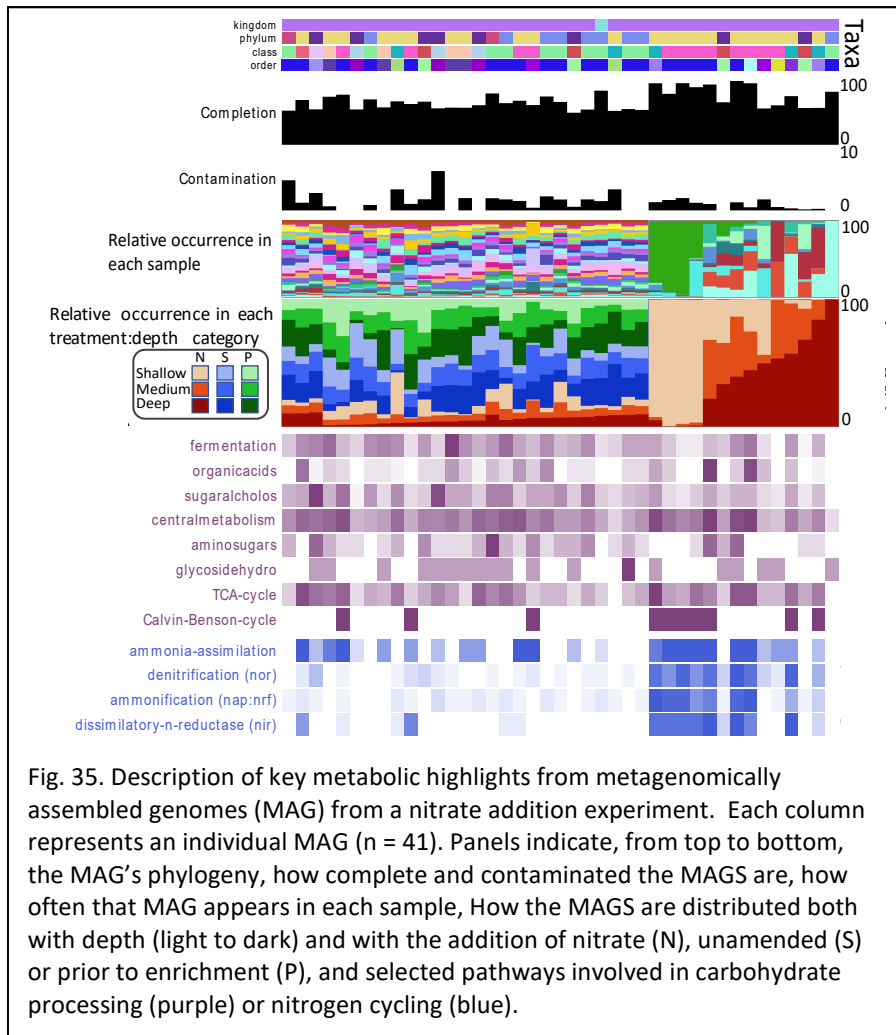


Fig. 35. Description of key metabolic highlights from metagenomically assembled genomes (MAG) from a nitrate addition experiment. Each column represents an individual MAG (n = 41). Panels indicate, from top to bottom, the MAG's phylogeny, how complete and contaminated the MAGs are, how often that MAG appears in each sample, How the MAGs are distributed both with depth (light to dark) and with the addition of nitrate (N), unamended (S) or prior to enrichment (P), and selected pathways involved in carbohydrate processing (purple) or nitrogen cycling (blue).

and other anaerobic respiratory pathways.

Among the more ubiquitously distributed genomes there were numerous genomes that contained the capacity for denitrification and methanogenesis, indicating a diverse array of metabolic strategies. Most noteworthy, however, was the dramatic response in the shallow sediments from the nitrate addition treatments, where five genomes were predominant (Fig 35). These genomes are noteworthy due to the abundance of genes associated with carbon fixation and denitrification, suggesting that autotrophic denitrification may be more important in salt marsh sediments under high nitrate loading than had previously been recognized.

#### Next Steps - Future

work is focusing on assessing these genomes from a pan-genomic perspective, while adding more genomes through novel microbial isolation methodology. The genomes from these isolate collections can be used to better understand how salt mash biogeochemistry will respond to global change drivers through genome network models that allow us to expand our work to the ecosystem scale.

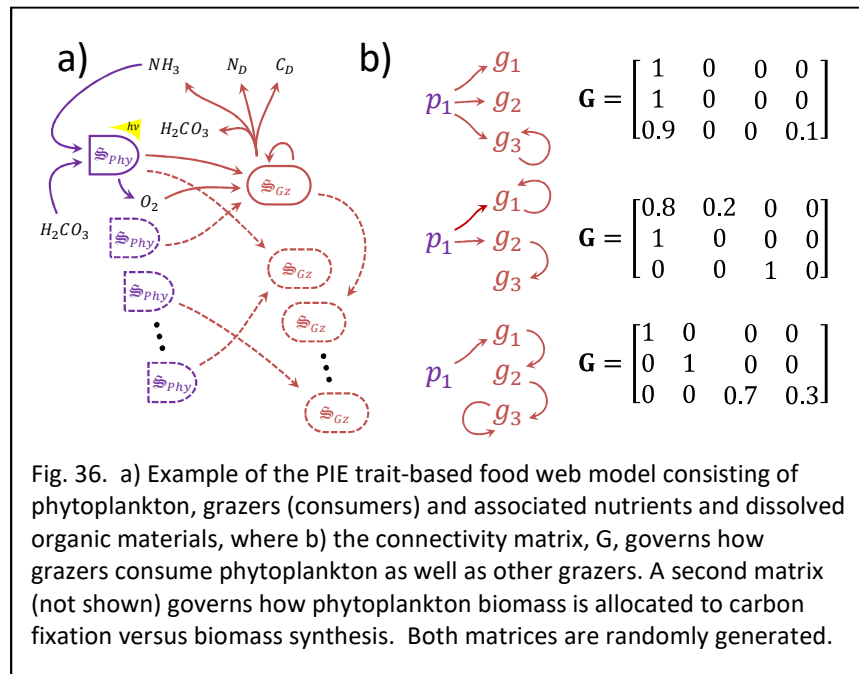
#### Trait-based modeling of biogeochemical cycles

We have been developing a trait-based model to describe estuarine biogeochemistry at PIE that is based on previous models that are guided by an optimization-based approach (Vallino & Huber 2018). One of the disadvantages of classic biogeochemistry models is that they often fail when subject to new environmental conditions that the models were not calibrated for. Yet, extrapolation to new environmental conditions is the primary objective of most scientific modeling. The main reason classic PZN-like models often fail is that predicting how community composition will change following a change in an environmental driver is extremely difficult. As communities change composition, such as in response to eutrophication, classic models must be reparametrized to capture the growth kinetics of the newly established community, but if the change in community composition cannot be predicted, then the kinetics will be incorrect.

Trait-based models solve the changing community composition problem by simply populating a model with many functionally similar organisms that cover the expected range of possible growth kinetics, then allow those organisms to compete in-silico in a manner similar to Darwinian selection. The primary design challenge with trait-base models is understanding trait trade-offs and food web connectivity. Without appropriate trade-offs between certain traits, models will be populated with “super bugs” that are not found in nature and will end up dominating a simulation. For instance, if the maximum growth rate and substrate affinity parameters are not properly correlated, random selection of these traits will produce organisms that can grow extremely fast but can also take up nutrients down to nanomolar concentrations, which is inconsistent with observations. Consequently, we have developed an adaptive Monod kinetics model that properly correlates maximum substrate uptake rate, substrate affinity and growth efficiency that can model microbial communities under both eutrophic and oligotrophic conditions (Vallino 2011).

More recently we have been exploring how food web connectivity impacts trait-based models in PIE. Since trait-based models by design contain 100s or more organisms for each functional group (such as photoautotrophs, sulfate reduces, etc.), a predation matrix that connects predators to prey must be specified. In a simple, 0D, test model, we found that changing the nature of the predation matrix has a marked effect on the community dynamics and resource use by the microbial community. In particular, food webs that are highly interconnected, so that predators can eat all prey, as well as all other consumers, exhibit stable community dynamics, but do not utilize resources effectively (i.e., lower overall productivity); however, in food webs that are composed of a large number of weakly interconnected specialized sub food-webs, we find communities exhibit unstable dynamics, but more effectively utilize resources.

To study how food web connectivity in trait-based models impacts biogeochemistry and community dynamics in a model more relevant to PIE, we have coupled our 1D transport model for PIE (Vallino et al. 2005) with a simple autotroph-heterotroph trait-based model (Fig. 36).



Microbial growth kinetics for both autotrophs and heterotrophs is based on models that we have used to study how energy is dissipated by the microbial community in a coastal meromictic pond that can be described as a “vertical estuary” (Vallino and Huber 2018). In this metabolic-based model, autotrophs are represented by two reactions, one responsible for fixing  $CO_2$  using solar radiation, and a second reaction that converts photosynthate into phytoplankton biomass. Two traits govern the

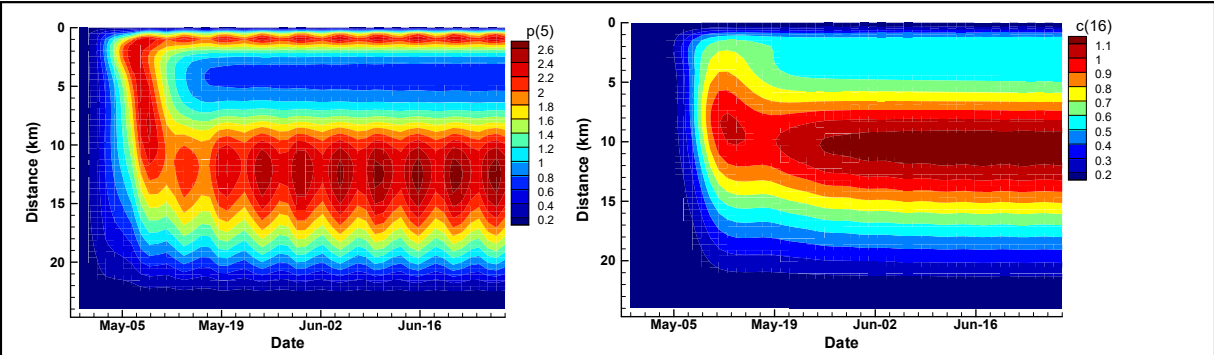


Fig. 37. Example simulation of the PIE 1D trait-based model. In this simulation, the 1D estuary (0 to 24 km on y-axis, where 0 starts at the freshwater endmember) was populated with 50 primary produces and 50 consumers and allowed to run for 60 days starting in spring. The 100 plankton were randomly assigned a thermodynamic growth efficiency parameter, and the consumer matrix  $\mathbf{G}$  was randomly assigned values. The consumers could consume all prey, including all other consumers (i.e., highly connected network). While most plankton go extinct, roughly 6 remain in each functional group and are relatively stable over time. Shown here is primary producer #5 ( $p(5)$ , in  $\mu\text{M C}$  on left) and consumer #16 ( $c(16)$  in  $\mu\text{M C}$  on right).

phytoplankton, a thermodynamic efficiency parameter and a second parameter that specifies how biomass is allocated between the two reactions. Heterotrophs are governed by a thermodynamic efficiency parameter and a vector that specifies affinity for phytoplankton and other heterotrophs.

Initial simulations of our PIE 1D trait-based model appear to confirm our preliminary 0D results regarding food web connectivity matrix. In these simulations we populated the 1D model domain with 50 primary producers and 50 consumers that were randomly assigned thermodynamic efficiencies between 0 and 1, and randomly populated the consumer-prey vectors (we also randomly generated how biomass was partitioned between the two primary producer reactions). In one set of simulations we allowed the

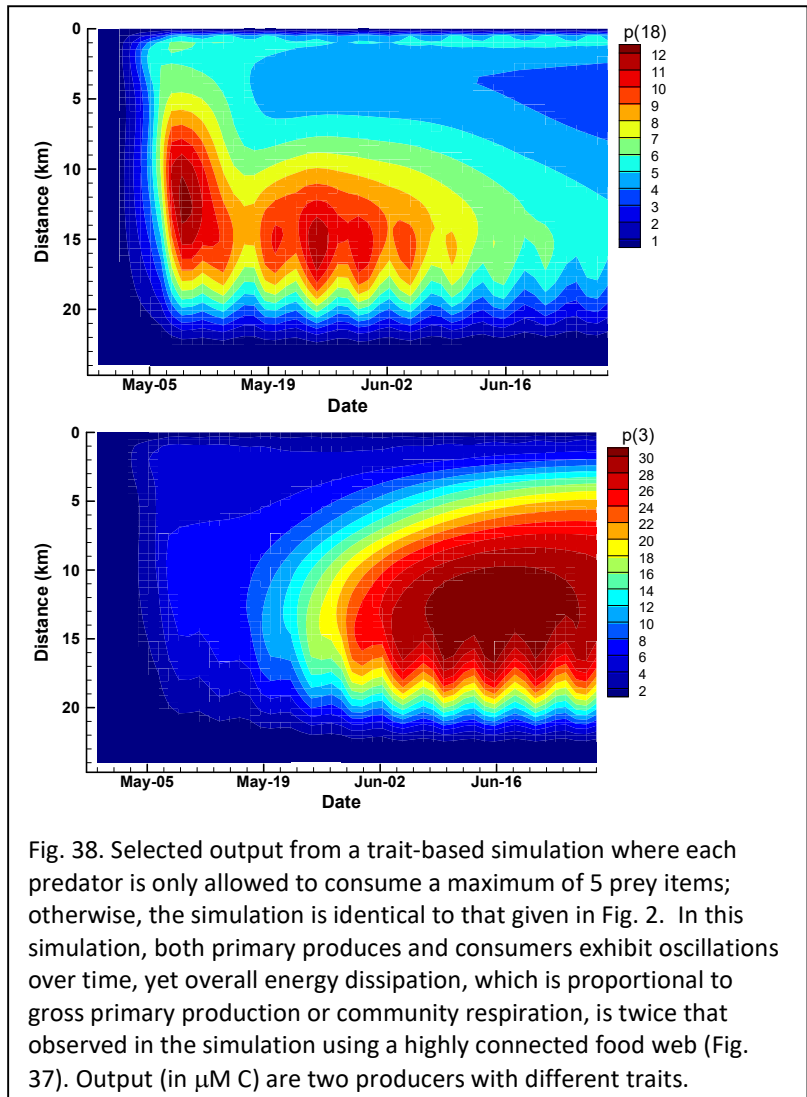


Fig. 38. Selected output from a trait-based simulation where each predator is only allowed to consume a maximum of 5 prey items; otherwise, the simulation is identical to that given in Fig. 2. In this simulation, both primary produces and consumers exhibit oscillations over time, yet overall energy dissipation, which is proportional to gross primary production or community respiration, is twice that observed in the simulation using a highly connected food web (Fig. 37). Output (in  $\mu\text{M C}$ ) are two producers with different traits.

consumers to consume any prey item, which produced rather stable communities over the 60-day simulations following in-silico natural selection (Fig 37). In another set of otherwise identical simulations we limited the consumers to only 5 randomly selected prey. Unlike the highly connected food web (i.e., Fig. 37), the weakly connected microbial community generated rather unstable community dynamics (Figl 38); however, resources utilization, as measured by whole-estuary free energy dissipation, was twice that of the first simulation (1230 vs 586 TJ).

**Next Steps** We plan to extend our trait-based modeling approach to include more functional groups (sulfate reducers, denitrifiers, etc) so that we can compare model output to observations of community structure and function revealed by genomic surveys, as described above, which will also reveal aspects of community stability that will be important for developing algorithms for predator-prey matrix construction. The model will also be extended 1D vertically into the marsh sediments to complement subsurface biogeochemistry and community composition studies.

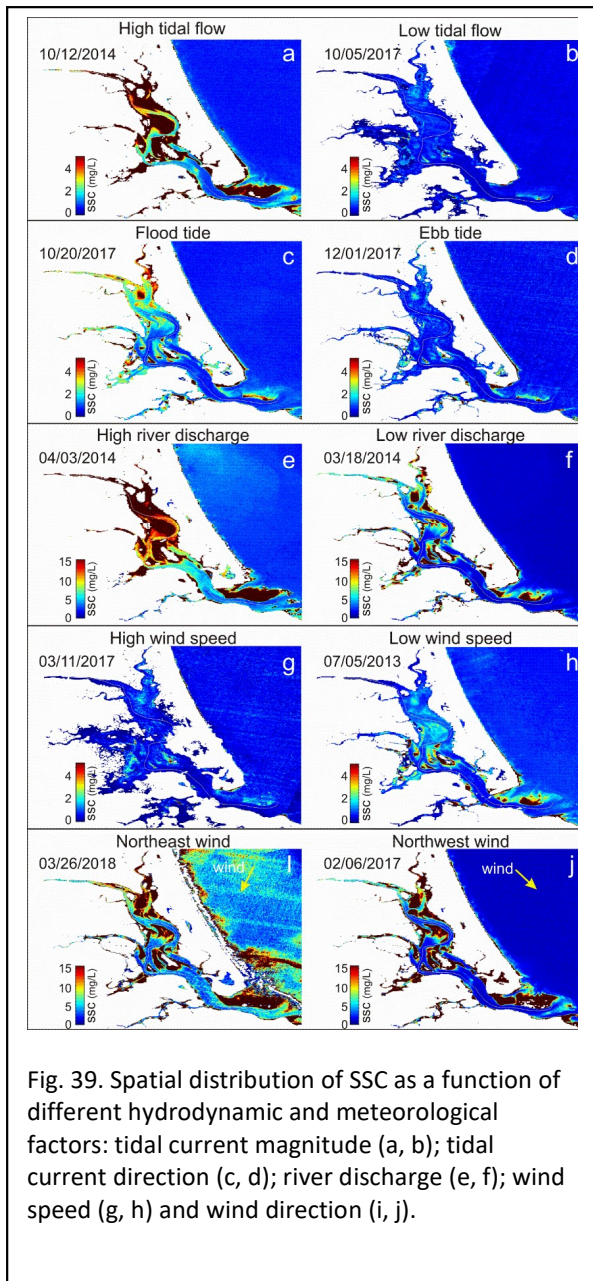
## **V. Collaborative, Cross-Site and Synthesis activities**

### **Measuring spatio-temporal change – Cross-Site**

Gil Pontius and his assistants have been working with collaborators across LTER sites to develop methods to analyze the spatial patterns of temporal change on landscapes. We are focusing on coastal change, in particular, the change among marsh types and the movement of the boundary between land and water. We are testing the generalizability of various methods by seeing how the methods perform with data from Plum Island Ecosystems (PIE), Georgia Coastal Ecosystems (GCE), and Virginia Coast Reserve (VCR). The Baseline & Transect method is one popular technique to measure change of boundaries (Jackson, Alexander, and Bush 2012). We have found that the Baseline & Transect method requires numerous subjective decisions that can influence the results. Furthermore, the Baseline & Transect method is ill suited for some segments of the PIE coastline, such as where a peninsula exists one time point but not at another time point due to erosion or sedimentation or where islands form and disappear. As an alternative, we have developed a straightforward Overlay method that overcomes the problems of the Baseline & Transect method. Our Overlay method overlays maps from various time points so that each part of the spatial extent is a unique combination of land or water at each time point. Doctoral research assistant, Sam Khallaghi, won an award at the 2019 meeting of the American Association of Geographers for his research that compares the two methods. We have developed additional methods to characterize change among categories during several time intervals (Pontius Jr 2019; Pontius Jr, Huang, et al. 2017; Pontius Jr, Krithivasan, et al. 2017; Pontius Jr and Santacruz 2014; Huang et al. 2018). We are now applying and developing those methods further to characterize changes among marsh types.

### **Remote sensing of suspended sediments – collaboration with NASA DEVELOP**

Working with Cedric Fichot (BU), we have used high-spatial-resolution maps of suspended sediment concentration (SSC) derived from remote sensing images to help evaluate the relative influence of river flow, tides and winds on SSC dynamics of Plum Island Sound. Landsat-8 Operational Land Imager and Sentinel-2A/B Multispectral Instruments imagery revealed how the spatial distribution of SSC changed for a representative range of flood- and ebb-tide conditions while also capturing the effects of Nor'easter storms and river-floods (Fig. 39). In general, SSC decreased seaward along the estuary, and was higher during the spring season because of increased river discharge associated with snowmelt. Tidal asymmetry of SSC also enhanced



sediment resuspension during flood tides, possibly favoring deposition on marsh platforms. The interplay between river and tidal flows dominated the dynamics of SSC, whereas wind-driven resuspension had more moderate effects. Together, water level, water-level rate of change, river discharge and wind speed were able to explain > 60% of the overall variability in the average SSC along the main channel of the estuary, thereby facilitating future prediction of SSC from these readily available variables (Zhang et al. 2019b).

### Coastal SEES: Science, Engineering, and Education for Sustainability

PIE, along with VCR and GCE, is just finishing a Coastal SEES grant focusing on the vulnerability and sustainability of tidal wetlands to climate-driven change, and the feedbacks between those wetlands and the adjacent coastal communities as related to the feasibility and socio-economic benefits of adaptation actions.

### Participation in LTER synthesis working groups

PIE investigator David Johnson is a member of the CoRRE group (Community Responses to Resource Experiments, <https://corredata.weebly.com/>), an LTER data synthesis group. CoRRE has compiled 101 datasets of resource experiments on grasslands – including salt marshes – from across the globe to understand the impact of global-change drivers on community structure. These datasets are largely from LTER sites, including PIE.

Jarrett Byrnes is a member of the NCEAS LTER-NCO Scaling-up productivity responses to changes in biodiversity working group. He is leading analyses to see if long-term time series of biodiversity change show disproportionate loss of rare species and whether such loss leads to changes in ecosystem function. He is also using techniques from econometrics to develop methods for the analysis of long-term biodiversity monitoring data to make causal attribution of changes in biodiversity or changes in ecosystem function due to observed drivers.

## VI. Broader Impacts, Education and Outreach

As detailed below, and in our proposal, the PIE-LTER has a robust program in outreach and education. Nearly every PI is involved in education at some level and most contribute to

outreach at the local, regional or national level. Highlights are listed below.

- ***PIE-LTER Schoolyard Program:*** Our K-12 Schoolyard program is led by Elizabeth Duff and held in collaboration with Mass Audubon. It provides experiential learning opportunities for students and teachers in their own backyard. The program serves approximately 1,000 students and 50 teachers per year in grades 5-12 in 10 schools. Each year students present their findings at a conference attended by PIE scientists. Initially focused on examining the changes in salt marsh vegetation due to tidal restrictions and hydrologic restoration, Ms. Duff has added a new climate change focus that will make use of the vegetation transects teachers and students have been measuring for the past 25 years. Resources for teachers, students and data are available at <https://www.massaudubon.org/get-outdoors/wildlife-sanctuaries/enticott/salt-marsh-project/> .
- ***Professional Development and Outreach:*** PIE scientists collaborate with Liz Duff on a summer professional development course for teachers and by working with them to produce “Data Nuggets” (<http://datanuggets.org/>) and lesson plans for teachers. Currently we have 9 data nugget lessons created in collaboration with local teachers and PIE scientists.
- ***Gulf of Maine Institute (GOMI):*** We collaborate with the Gulf of Maine Institute to provide training to teachers and help them develop environmental community-based stewardship projects throughout the Gulf of Maine. Education director Liz Duff also collaborates with this group and Giblin is chair of the board. Through this group we are currently working with 2 schools, Newburyport High School, and Lowell Middlesex Academy (LMA). LMA is a charter school for students who had previously dropped out of high school or are at risk to drop out. GOMI is providing training for the teachers in community based stewardship. PIE scientists are providing scientific support for teachers to develop their in-class programs. Through NSF’s Research Experience for Teachers (RET) we have funds to support 2 LMA teachers. Both schools are on the Merrimack River and we are connecting them through shared data collection activities.
- ***LTER-Children’s Book Series:*** Titled "Save our Stream", the story involves two children who learn about the lawn-stream connection from a field scientist they encounter, and take on the mission of educating their neighbors.
- ***Logan Science Journalism Course:*** Each year 6-8 journalists participate in the 12-day hands-on Logan Science Journalism program on coastal eutrophication. This program offers fellowships to mid-career science journalists and immerses them in ecosystem and global change science. During this cycle both Deegan and Giblin have served as course directors.
- ***Mentoring for Grads and Undergrads:*** During the summer, 10-14 undergraduate and graduate students work and live at our field house and many others come nearly daily from nearby colleges and universities. Students give presentations at the end of the summer on their work. This year we provided an opportunity for interested students to receive training in communication and outreach. Undergrads from Boston University and the MBL’s Semester in Environmental Sciences do part of their projects at the PIE site.
- ***Interactions with Policy Makers and Management Agencies:*** PIE scientists serve on a large number of advisory boards of organizations interested in marsh sustainability and on watershed

issues. Robert Buchsbaum serves as our local outreach representative and participates in many advisory groups including the Ipswich, Parker, Essex River Restoration coalition as a member of the Steering Committee. Wollheim is a member of the Ipswich Watershed Technical Advisory Committee. Fagherazzi advises managers of Parker River National Wildlife Refuge on the hydrology and geomorphology of salt marshes in Plum Island Sound and Giblin participates in meetings on salt marsh restoration and resilience with many local organizations. Other PIE scientists also take on major roles in watershed, fisheries, and marsh advisory committees.

●**Science and the Arts:** In collaboration with the Parker River Fish and Wildlife service, PIE has been working with two local artists to produce an exhibit on the relationship between marshes and their watersheds. Partial funding has been obtained already and we hope that the exhibit will be ready by the fall of 2020.

●**Social Media:** PIE now has a twitter account (@PIE\_LTER) and a logo.

## VII. Products

### 1. Peer Reviewed Journal Papers and Book Chapters

As of August 2019 PIE has a total of 387 published journal articles and 22 book chapters (the list is available at <https://pie-lter.ecosystems.mbl.edu/biblio>). During this last cycle (since 2016) we have published 58 journal articles. We have 4 additional accepted articles and book chapters and 5 papers in review.

### 2. Theses

PIE students have produced 17 Ph.D. theses, 50 master's theses and 22 undergraduate honors theses. Of these, 4, 10, and 3, respectively, are from the current award.

### 3. Datasets

PIE currently has 491 datasets publicly available in the EDI Data Portal, of which 133 represent geospatial GIS data associated with 26 towns of the Parker, Rowley and Ipswich River watersheds.

### 4. Websites and other Special Products

PIE's primary website is <https://pie-lter.ecosystems.mbl.edu/welcome-plum-island-ecosystems-lter>. In addition to the educational materials mentioned above, PIE scientists have produced a number of special products. For example, Chris Whitney created an App for citizens to report beaver ponds and an ArcGIS "Story Map" (<http://piebeaverponds.crowdmap.com>). Gil Pontius and students have produced videos on land change analysis methods in several languages and have made computer analysis tools freely available through R packages (<https://cran.r-project.org/web/packages>). The Marsh Equilibrium Model is currently being used by a number of state and federal agencies and enjoys a large user community. An interactive website (<http://jellyfish.geol.sc.edu/model/marsh/mem2.asp>) has attracted over 4,500 users and the model has an active R development community on GitHub.

## VIII. Data and Information Management

The goals of information management at PIE LTER are two-fold. One is to ensure data and information are available to the public in a timely manner to facilitate scientific synthesis, education and policy decisions. The second is to ensure research activities follow best practices for data management as related to stages of the data life cycle as outlined by DataOne, <https://www.dataone.org/data-life-cycle>. Data life cycle stages include planning, collection, assurance, description, preservation, discovery, integration and analysis.

### Data Life Cycle

*Planning* -Plans in research proposals, which describe experiments, observational and geospatial studies, are used to determine the types and formats of data that will be produced from research activities and coordinated with PIE data and information management. Data management of research projects is coordinated through an information management team. Hap Garritt, a senior research assistant (SRA) with The Ecosystems Center, MBL, has been the information manager (IM) since 1998 and has the responsibility for overseeing the overall integrity of the data and information system. The rest of the information management team consists of: Anne Giblin (Lead PI), Joe Vallino (PI-models), Robert Pontius (PI-GeoSpatial), Jane Tucker (SRA-Web), Liz Duff (Education), Jim Laundre (ARC-LTER IM support) and research staff with computer programming expertise. Management includes infrastructure support and guidance to process data for public availability on the PIE website (<https://pie-lter.ecosystems.mbl.edu/data>) and public national data repositories.

PIE data are discoverable through DataOne searches and available through the Environmental Data Initiative (EDI) Data Portal (<https://portal.edirepository.org/>) and the Biological and Chemical Oceanography Data Management Office (BCODMO) (<https://www.bco-dmo.org/>) both member nodes of DataOne. Eddy covariance data from PIE marshes are also available in the DOE Ameriflux Network (<https://ameriflux.lbl.gov>). Microbial genomic sequence data are available through accession numbers in NIH GenBank (<https://www.ncbi.nlm.nih.gov/genbank>). The repositories are very valuable for both discovering and accessing data and ensuring the long term preservation for future use.

PIE's website uses Drupal 7, a website content management system, which provides descriptions of research, education, and outreach, a data catalog, a personnel directory and publications associated with PIE. Several other LTER sites also use Drupal 7 in a collaborative known as Drupal Ecological Information Management System (DEIMS). The PIE website follows the guidelines for LTER information management systems ([http://im.lternet.edu/sites/im.lternet.edu/files/LTER\\_IMS\\_Guidelines\\_V2.2\\_20180709.pdf](http://im.lternet.edu/sites/im.lternet.edu/files/LTER_IMS_Guidelines_V2.2_20180709.pdf)).

Several meetings each year, (in particular the annual Spring PIE ASM) provide opportunities for PIE researchers to discuss our information system and coordinate needs for data management with their research. PIE researchers are reminded about contributions to the database several times during the year via email, teleconference calls and field sampling trips, in addition to announcements during our Spring ASM. The PIE IM (Garritt) attends LTER Information Management meetings and video teleconferences to participate in network activities and provide updates about LTER Network data standards and new initiatives. The PIE Executive Committee is responsible for dealing with researchers who do not submit data in a timely manner to the database. The PIE Executive Committee reserves the right to withhold funding or restrict services and facilities to researchers who do not contribute their PIE-related data.



*Collection and Assurance* - Each PI and associated research assistant/graduate student is responsible for their data collection, assurances of quality, data entry, validation and analysis, and data submission for their respective projects. This ensures that data and documentation have been reviewed and submitted by the data originators. With guidance from PIE IM, data are submitted using an Excel metadata and data form ([https://pie-ter.ecosystems.mbl.edu/sites/default/files/PIEMetadataBlank\\_0.xls](https://pie-ter.ecosystems.mbl.edu/sites/default/files/PIEMetadataBlank_0.xls)). The form provides helpful comments throughout to guide metadata entry. Data validation drop down lists for units, measurement scale, and number type are included to ensure consistency.

Observational long-term monitoring data, (ie. water quality, climate, water level, population dynamics) and long and short term experiments are submitted using the Excel form. Geospatial data (boundary, census, elevation and bathymetry, land use, land cover, parcels and zoning) are typically submitted via ArcGIS formatted data raster or vector data packages. Microbial genomic sequence data that have been submitted to GenBank are discoverable via a genomic reference file, (<https://pie-ter.ecosystems.mbl.edu/content/microbial-genomic-reference-data>) which is purely descriptive and includes the following information: bacterial genome citations, sequence accession numbers, study type, location, habitat and descriptive environmental conditions.

*Description* -An Excel metadata and data form is used as the initial step by researchers to submit data. After submission the PIE IM evaluates the data submission and uses a script (Excel macro) to check metadata and data for completeness, consistency, and formats with the goal of providing high quality data and metadata suitable for generating Ecological Metadata Language (EML) metadata. The Excel macro provides some metadata accuracy checks (standard units, package IDs, missing value codes, research locations), which are useful prior to submission to the EDI Data Portal where fairly extensive EML congruency checks are conducted. Upon a successful macro check the metadata are entered and data uploaded in the PIE web server (DEIMS) where the dataset, data sources, and other content (persons, research sites, research project) are updated or created. Once the data are in our website, an EML metadata (xml) file is generated for uploading the dataset and corresponding data source (csv or zip file) to the EDI Data Portal national repository. After the uploaded dataset is accepted in EDI, a Digital Object Identifier (DOI) is assigned and the dataset becomes publicly discoverable through DataOne.

*Preservation* - The PIE LTER website is hosted on a shared (with ARC LTER) Apache web server on an Ubuntu Linux 16.04 server. The server is a Lenovo server with software RAID 0. WebAdmin is used to help administer and maintain software updates. Security updates of Drupal and modules are maintained using Drush. Daily, weekly and monthly backups of the website and the SQL databases are made using Rsnapshots. Backups are stored on an external hard drive and weekly and monthly backups are also stored to a cloud backup. The Marine Biological Lab (MBL) maintains an intranet providing online storage and cloud backup for research projects and MBL has Office360 licenses for year-round researchers which include OneDrive for Business. Each researcher gets 5 TB of online storage with the ability to share folders and files with external researchers. As stated previously, PIE data are available in various public long-term national data networks and repositories, which ensures long term preservation.

*Discovery*- PIE adheres to the LTER Network Data Access Policy, <https://lternet.edu/data-access-policy>, with regard to data availability, metadata standards and data use agreements. PIE LTER researchers are required to contribute data to the PIE LTER. It is recognized that

investigators on PIE LTER have first opportunity for use of data in publications but there is also the expectation for timely submittal of datasets for incorporation into the PIE LTER data system and public data repositories. PIE strives to make data available within 1-2 years. The variability in time is dependent upon the time required for sample analysis and corresponding QA/QC of data and metadata. Data such as water quality, water level, discharge and meteorological observations from data-logging instruments and data that do not require a great deal of post-collection analysis are available within 3-6 months of collection. Very large datasets, > 5GB, such as raw LiDAR are available upon request in addition to non-tabular scanned aerial imagery and maps. PIE data are easily accessible and downloadable via our website and the EDI Data Portal per the PIE data use agreement, <https://pie-lter.ecosystems.mbl.edu/content/pie-lter-data-use-agreement> and as outlined under the Creative Commons Attribution 4.0 International License, <https://creativecommons.org/licenses/by/4.0>. We request that datasets be cited and PIE LTER funding source and NSF be acknowledged in published papers.

The PIE Data Catalog, <https://pie-lter.ecosystems.mbl.edu/data>, includes dataset search capabilities using keywords, LTER Core areas and PIE Research Areas to provide easy access to datasets of interest. PIE routinely contributes to network databases of ClimDB/HydroDB, Personnel, Bibliography and recently to the EDI ecomDP community survey data.

*Integration and Analysis* -PIE researchers use a variety of software for data integration and analysis depending upon the data type research goals. Excel spreadsheets are routinely used for chemical analyses, data entry and basic statistics. Larger datasets such as marsh sediment erosion table elevation heights are analyzed with SAS. Matlab is used routinely in eddy covariance analysis. ESRI ArcGIS and Clark Labs TerrSet IDRISI GIS Analysis and Image Processing software are used for geospatial data. We use EndNote for managing bibliographies and publication citations. EndNote has the capability of exporting file formats for importing publications to our Drupal website and BibTex formats for submission to the LTER Network Communications Office (NCO) and NSF.

#### Accomplishments 2016-2019

- The PIE Drupal 7 website went live in December 2017, providing a much better content relationship system which is easily searchable across research areas.
- Bibliography and Personnel updates were provided to the LTER NCO for use in LTER 40 year review.
- We had a higher percentage of successful dataset uploads to EDI that incorporate new congruency metadata checks.
- We now provide eddy covariance data uploads to the Ameriflux network.

#### Future 2019 -2022

- During 2019-2020 we are planning to move our Drupal 7 website to Drupal 8 as Drupal 7 will be losing support in Nov 2021.
- We will collaborate with other DEIMS sites to create a simpler process of creating metadata content in Drupal 8 (2020).
- We will continue R script development for analysis of long term datasets such as climate, water quality and water level.
- We will upload PIE ClimDB/HydroDB data to CUAHSI in collaboration with EDI efforts.

- We will incorporate the new currently unreleased EML 2.2 fields for research project into DEIMS to provide more specific details about project funding associated with various datasets.
- Garritt joined a new LTER working group (Aug 2019) formed to address non-tabular data and how to accommodate them in EDI for more accessible public access. PIE has many very large datasets associated with LiDAR and many historical maps and aerial photos which need to be discoverable and accessible via data repositories.

## **IX. Partnerships and Shared Funding**

The PIE LTER benefits from two types of partnerships. The first is other funded grants where the research fits into PIE goals, and where one or more of the PIs on the grant is a PIE LTER investigator. Some of these are cross site grants. In some cases, such as with the long running TIDE project (Deegan PI) long-term datasets are jointly maintained and the LTER assumes a role in data collection even when the project is not active. A complete list of grants, lead PIs, funding and the grant dates is given in Appendix 1.

The second type of partnerships is collaborations which do not include funding. A few of our key partnerships include Mass Audubon for our schoolyard program and the Gulf of Maine Institute as described above under education. Other important partners include:

***Parker River Fish and Wildlife Refuge (federal agency) and Essex County Greenbelt (NGO):*** Many of our research sites are on land owned by these two groups and we partner with them on research, education, and outreach.

***Ameriflux:*** Data collected at our two eddy covariance sites are being uploaded to the Ameriflux data base. We are also participating in Ameriflux 'year of methane', and are currently measuring methane using a LI-7700 loaned to us through Ameriflux.

***Science Policy Exchange:*** (<https://science-policy-exchange.org/>), is a consortium of four LTER sites and six research institutions. The mission is to inject more science into environmental policy.

## **X. Site Management, Broadening Participation, Transition Planning**

### **Site management**

Our project management is described in detail in the proposal and we have largely followed those plans. Giblin is the lead PI and she works closely with an executive committee on project management. The Executive Committee consists of the leads of each major research area: watersheds (Wil Wollheim); geomorphology (James Morris); biogeochemistry (Nathanial Weston); consumers (Linda Deegan); and modeling (Joseph Vallino). There is also one rotator, currently Jarrett Byrnes. The committee meets in person twice a year and regularly by conference call. The Executive Committee is consulted on all major decisions and helps choose new scientists for leadership positions. Each member of the executive committee also makes sure that long-term data sets are being collected in their research area and helps writing annual reports.

During this first period of PIE IV we engaged with three rotating advisory committees to address specific aspects of each of the program areas in addition to seeking feedback on the

overall research program. The panel recommended that we form a standing committee rather than rotating committees, and we are now choosing three members from among the rotators to form a standing advisory committee to serve for the remainder of the grant.

### **Transition Planning**

We anticipate 1 or 2 changes in the leadership of our research areas during the next funding round. Leadership changes will be guided by the Executive Committee. We are currently mentoring scientists on the project we believe can fill this role. Giblin will lead the preparation of the next proposal with one to two additional co-PIs and assistance from the Executive Committee. All scientists will be involved in the initial planning stages to assure that the ideas of the newer scientists are represented and incorporated. MBL will also shortly be recruiting a new scientist who we expect will be able to take over PIE leadership in the future. It is anticipated that Giblin will step down early in PIE V and the new PI will take over, or take over with a Co-PI.

### **Broadening Participation**

PIE-LTER seeks to increase diversity. PIs and senior personnel are 38% female and the percentage of women is higher in the ranks of younger faculty, post-docs and students. Some of these people will be moving into leadership ranks in the next cycle (Table 1). Recruiting minority investigators and students has been more difficult. Through connections with U. Mass Boston, and the U. of Chicago we have been having more success recruiting a diverse applicant pool of undergrads and grad students. We have the greatest diversity in our schoolyard program where we work with several school that have a majority minority population.

*Table 1. Break down of the numbers of individuals holding various positions at PIE and the % of each pool that is female. The number of unique institutions in each category is also shown.*

<b>Category</b>	<b>Number</b>	<b>% Female</b>	<b>Unique Institutions</b>
Lead and Co-PIs	5	40%	4
Other Senior personnel	16	37%	9
Other Faculty	4	50%	3
Post-Docs	5	80%	
Grad Students	34	62%	
Undergrads	72	69%	
REUs	6	67%	
Technicians	17	76%	
RETs	2	100%	

## XI. Literature

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**XII. Appendix I.** Leveraged funding for PIE IV. Note some grants listed as ending before 2016 are included because post-docs or students continued into 2016.

Official title of grant	Last-name	Funding Agency	Total award, in dollars	Start date	End Date	NOTES
Collaborative Research: MSB: The Role of Sulfur Oxidizing Bacteria in Salt Marsh C and N Cycling	Cardon	NSF-DEB	510,333	9/1/2011	8/30/2014	
ETBC Collaborative Research: Feedbacks between nutrient enrichment and intertidal sediments: erosion, stabilization, and landscape evolution	Fagherazzi	NSF-OCE	\$897,134.00	9/1/2009	8/31/2014	
Eutrophication Effects on Sediment Metabolism and Benthic Algal-bacterial Coupling: An Application of Novel Techniques in a LTER Estuary	Stanley	NSF-OCE	786,295	9/1/2012	8/31/2015	
Impact of hurricane Sandy on the salt marshes of Chincoteague Bay, Virginia, and Barnegat Bay, New Jersey	Fagherazzi	USGS	\$99,903	1/1/2014	12/31/2015	with VCR
The impacts of increased nitrogen loadings on decomposition in salt marshes: Does eutrophication enhance marsh accretion or erosion?	Giblin	NOAA	182,358	2/1/2014	1/31/2016	includes match
Application of thermodynamic theory for predicting microbial biogeochemistry	Vallino	NSF-EAR	203,658	4/15/2015	3/31/2016	related to model development
Collaborative Research: Strengthening the scientific basis for decision making: Advancing sustainability science and knowledge-action capacities in coupled coastal systems	Nisbet	NSF	217,524	1/1/2013	12/31/2016	Wollheim portion
Interaction Among Climate, Land Use, Ecosystem Services and Society	Nisbet	NSF	1,600,000	1/1/2011	12/31/2016	Wollheim portion
Ecosystem evolution and sustainability of nutrient enriched coastal saltmarshes	Fagherazzi	NSF	108,262	3/15/2014	2/28/2017	with VCR
Using geomorphology and animal "individuality" to understand 'scape-scale predator distributions. (Ryland Taylor)	Mather	NSF	63,963	1/1/2015	12/31/2017	
Collaborative Research: RUI: Human alteration of sediment delivery to the coast – legacies of land use, coastal wetland accretion, and future vulnerability to sea level rise.	Morris	NSF-BIO	83,125	8/1/2015	7/31/2018	collaborative, USC portion
Coastal SEES Collaborative Research: A cross-site comparison of salt marsh persistence in response to sea-level rise and feedbacks from social adaptations	Giblin	NSF-OCE Coastal SEES	309,021	8/5/2014	8/4/2018	collaborative with GCE and VCR, McGlathery overall lead
Ecosystem Evolution and Sustainability of Nutrient Enriched Coastal Saltmarshes.	Deegan	NSF_DEB	1,651,140	4/1/2014	4/1/2019	
Northeast Climate Science Center.	Deegan	Dept. of Interior	528,729	10/1/2012	6/30/2019	
Collaborative Research: RUI: Human Alteration of Sediment of Delivery to the Coast - Legacies of Land use, Coastal Wetland Accretion, and Future Vulnerability to Sea Level Rise	Weston	NSF-DEB	665,660	8/1/2015	7/31/2019	
Community Science Program: Nitrate in coastal waters: shifting the balance from carbon sink to carbon source	Bowen	DOE	87,654	9/1/2017	8/31/2019	
Estimating Spatially Explicit Water Quality Benefits throughout River Systems: Development of Next Generation Stated Preference Methods Using National Probability Samples and Online Labor Pools.	Johnston	EPA	200,000	1/1/2019	12/31/2019	Wollheim portion
Developing a Miniaturized In-situ Sensor Technology for Simultaneous Measurements of Seawater Dissolved Inorganic Carbon and pCO <sub>2</sub>	Wang	MIT Sea Grant	\$183,023	2/1/2017	1/31/2020	
Collaborative Research: Predicting the Spatiotemporal Distribution of Metabolic Function in the Global Ocean	Vallino	NSF-OCE	510,916	4/1/2016	3/31/2020	related to model development
SG: Ecological insights from range-expanding populations	Johnson	NSF-BIO	150,000	6/1/2018	5/30/2020	
"MRI: ACQUISITION OF AN INDUCTIVELY COUPLED PLASMA MASS SPECTROMETER (ICP-MS) FOR ECOLOGICAL, ENVIRONMENTAL, AND ECOSYSTEM-LEVEL RESEARCH"	Weston	NSF-DBI	286,947	9/1/2017	8/31/2020	
Community Science Program: Nitrate in coastal waters: shifting the balance from carbon sink to carbon source	Bowen	DOE	47,645	9/1/2018	8/31/2020	
Impact of hurricane Sandy on the salt marshes of Chincoteague Bay, Virginia, and Barnegat Bay, New Jersey	Fagherazzi	USGS	275,000	9/1/2016	8/30/2021	with VCR
Delta X	Fagherazzi	NASA	651,896	6/1/2019	05/31/2022	with VCR
Optimization of marsh restoration for storm surge abatement and sea level rise	Morris	NOAA	230,000	11/1/2014	4/31/2018	
" Collaborative Research: TIDE: Legacy effects of long-term nutrient enrichment on recovery of saltmarsh ecosystems"	Deegan	NSF_DEB	\$1,590,061	5/1/2019	5/1/2021	