PROJECT SUMMARY

Overview:

The Plum Island Ecosystems (PIE) LTER is developing a predictive understanding of the response of a linked watershed-marsh-estuarine system in northeastern Massachusetts to rapid environmental change. Over the last 30 years, surface sea water temperatures in the adjacent Gulf of Maine have risen at 3 times the global average, rates of sea-level rise have accelerated, and precipitation has increased. Coupled with these changes in climate and sea level are substantial changes within the rapidly urbanizing watersheds that influence water, sediment, and nutrient delivery to the marsh and estuary. In PIE IV our focus is on: Dynamics of coastal ecosystems in a region of rapid climate change, sea-level rise, and human impacts.

Intellectual Merit :

We will test how internal feedbacks within the marsh-estuary ecosystem influence the response of geomorphology, biogeochemistry, and food webs to three major drivers: climate, sea-level rise, and human alteration of the watershed. We anticipate large changes in the geomorphology of the marsh and estuary over the next several decades. We hypothesize that major feedbacks are exerted through sediment dynamics, changes in hydrology, alterations of carbon and nitrogen cycles, species interactions, and species introduction or loss due to warming. Positive biogeomorphic feedbacks within the marsh ecosystem will likely contribute to marsh persistence while sea level rises, but we hypothesize that PIE is moving from a predominantly high-elevation marsh to a lower elevation marsh, with less overall wetland, more open water, and more marsh edge. These changes will greatly impact estuarine biogeochemistry, primary production, and community dynamics. PIE IV will address three questions: 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?; Q2) How will changing climate, watershed inputs, and marsh geomorphology interact to alter marsh and estuarine primary production, organic matter storage, and nutrient cycling?; and Q3) How will key consumer dynamics and estuarine food webs be reshaped by changing environmental drivers, marsh-estuarine geomorphology and biogeochemistry? Cross-system comparisons with other LTERs along gradients of temperature, species composition, tidal range, and sediment supply will further our understanding of long-term change in coastal ecosystems.

Broader Impacts :

This work will advance our understanding of how the structure and function of coastal ecosystems will be altered over the next several decades and beyond. Because of their position at the land-sea interface, coastal ecosystems are particularly threatened by human activities in watersheds and to sea-level rise. Our research will address both fundamental ecological questions as well as provide critical information on how to manage these systems. For example, it will help us understand how species changes in a complex interaction network result in changes to the abundance of key species, food web structure, and energy flow. PIE research will also improve our understanding of the importance of the coastal zone to regional and global carbon and nitrogen budgets and advance our ability to model biogeochemistry at the ecosystem scale in a spatially explicit framework. Finally, it will provide a greater mechanistic understanding of biogeomorphic feedbacks that will be essential in future conservation efforts. We will continue our award winning Schoolyard program, "Salt Marsh Science", which serves over 1,000 students in grades 5-12 in ten schools each year. In collaboration with the Gulf of Maine Institute we are developing a new initiative with local Middlesex Community College. By providing flexible paid internships with academic credit, we will be able to reach students from economically and ethnically diverse backgrounds who might not otherwise consider STEM careers. Outreach is important to PIE scientists. Activities include scientific collaborations outside PIE and with local, state and federal agencies, involvement in the MBL science journalism program, and partnership with Mass CZM in conducting marsh elevation surveys. PIE scientists currently serve on panels or advisory groups for EPA, NOAA, USFWS, and many state and local agencies. All data collected by the PIE LTER are centralized and made available to the public through our web site http://pie-lter.ecosystems.mbl.edu/.

I. PROJECT DESCRIPTION

The coastal ecosystems of the Plum Island LTER are in an area of the world that is rapidly changing. Over the last 30 years, surface sea water temperatures in the Gulf of Maine have risen at 3 times the global average; over the last decade warming has increased 7 fold to an average of $0.23^{\circ}C\ y^{-1}$ making the Gulf of Maine one of the fastest warming regions in the global ocean (Pershing et al. 2015). The newest climate models predict that the warming trend will continue (Saba et al. 2016). The warming is also associated with a shift in the Gulf Stream that affects local sea level. Our area is experiencing high rates of sea-level rise that appear to have accelerated over the last 20 years to over 4 mm y^{-1} compared to the long term average of 2.8 mm y^{-1} over the last century (NOAA Boston Tide Gauge). Precipitation has increased 20% over the last 70 years, snowpack has decreased, snowmelt is occurring earlier and rainfall has become more variable - all of which have affected the timing and magnitude of freshwater discharge to the estuary. Suburbanization with its increase in impervious area and municipal water use policies has further contributed to variability and long-term changes in water transport (Wollheim et al. 2013) as well as sediment, nutrient and organic matter inputs to the estuary. The re-establishment of beavers and the upcoming removal of human dams will alter sediment, nutrient and water inputs while ongoing suburbanization will continue to increase water and inorganic nutrient input to streams and rivers.

The Plum Island Ecosystems (PIE) LTER site consists of a linked watershed-marsh-estuarine system located north of Boston, Massachusetts. 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 marshes and the estuarine waters are influenced by three rivers: the Ipswich, the Parker and the Rowley, which collectively drain over 550 km^2 of upland (Fig. 1).

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 south of Cape Cod, Massachusetts, a historic geographic barrier. For example, our marshes currently lack all of the invertebrate species implicated in consumer controls on marsh primary production in more southerly marsh systems (Pennings and Silliman 2005), although this may be changing. The coastal system is macrotidal, with tidal excursions often exceeding 3 meters as opposed to more southerly US Atlantic marshes where tidal ranges are typically lower than 2m.
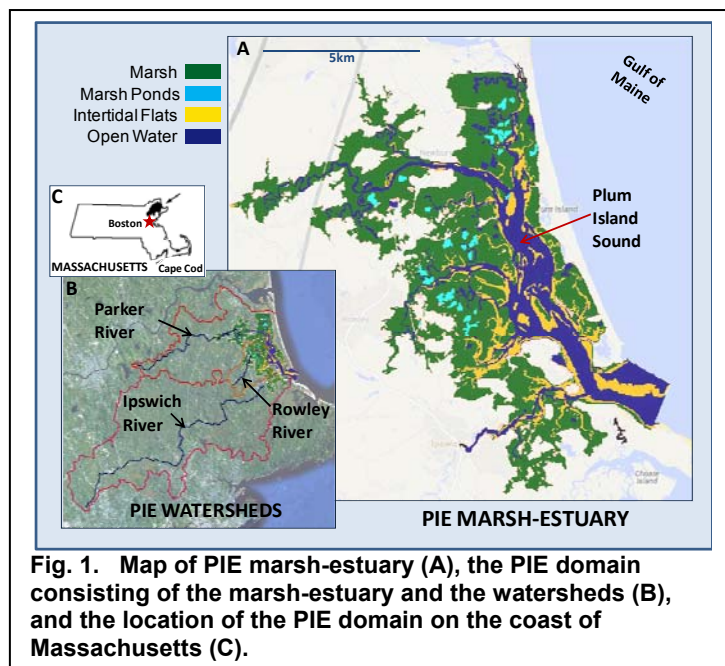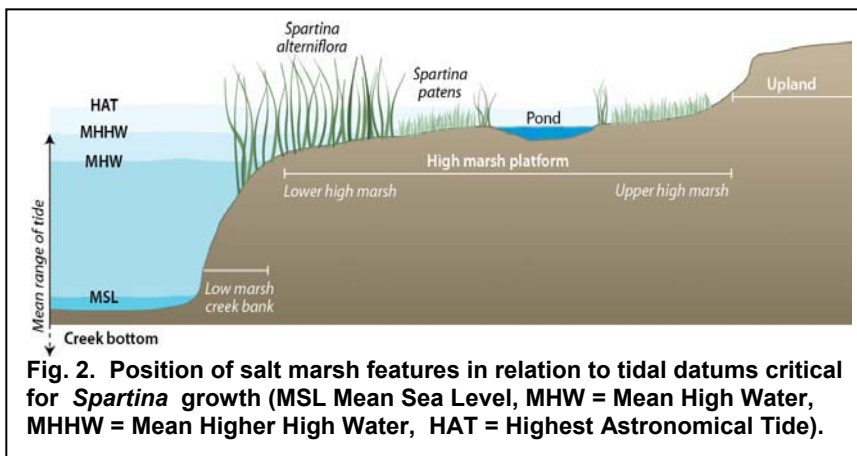

Fig. 1. Map of PIE marsh-estuary (A), the PIE domain consisting of the marsh-estuary and the watersheds (B), and the location of the PIE domain on the coast of Massachusetts (C).

History of Previous Research Since its inception in 1998, the Plum Island Ecosystems LTER has 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.* A primary hypothesis tested in PIE I was that the interaction of inorganic nutrients with the quality and quantity of organic carbon and nitrogen plays an important role in determining the trophic structure, production and efficiency of estuarine food webs. Our work did not support this hypothesis, rather we found that *hydrology* was more important than nutrient:organic matter input ratios in structuring the food web by controlling the residence time of water and hence relative importance of benthic vs planktonic foodwebs. The residence time effect varied widely depending upon the physical characteristics of different parts of the estuary.
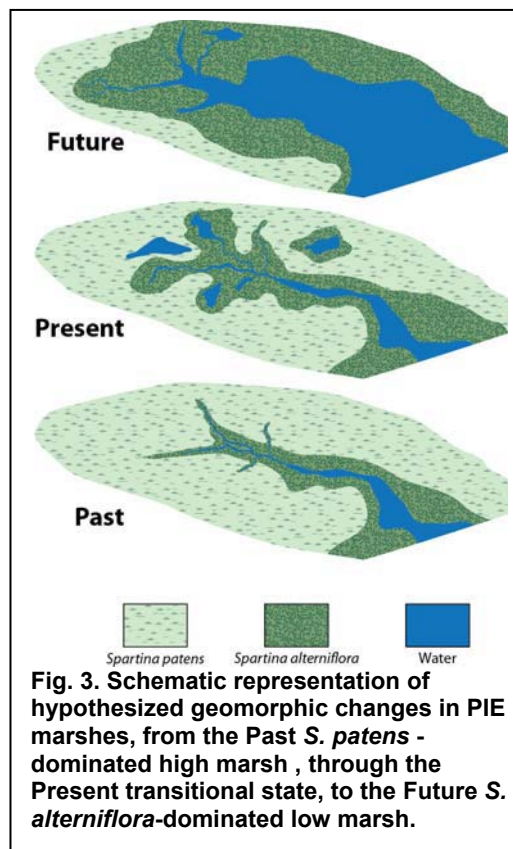
In PIE II we focused more heavily on the importance of the interactions of changing nutrient, water and organic matter inputs with the "*hydrologic and geomorphic template*" (e.g., places where residence time was set by bathymetery). However, during PIE II it became evident that we had to incorporate *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 impacts organic matter and nutrient transformations in linked watershed and coastal ecosystems. *Our overarching 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.* Understanding how landscapes and seascapes evolve and change, and how those changes interact with ecosystem processes, is both a fundamental science question and a critical management question for policy makers. We continued to study the impact of *temporal change and variability* in climate, sea-level rise and human activities on ecological processes in our long-term monitoring and initiated new activities that explored how these changes affect the way ecosystems and habitats within the landscape are arranged and connected.

Fig. 2. Position of salt marsh features in relation to tidal datums critical for *Spartina* growth (MSL Mean Sea Level, MHW = Mean High Water, MHHW = Mean Higher High Water, HAT = Highest Astronomical Tide).

This Proposal

In PIE IV our focus is on: *Dynamics of coastal ecosystems in a region of rapid climate change, sea-level rise, and human impacts*. This work naturally builds from previous research but with a greater focus on critical areas including sediment dynamics, species interactions, and the role warmer water plays on species changes within our system. We will continue to examine how external drivers alter the geomorphology, biogeochemistry, and consumer dynamics and food webs of coastal ecosystems. We anticipate large changes in the geomorphology of the marsh and estuary over the next century and beyond. PIE appears to be moving from a predominantly high-elevation marsh system dominated by *Spartina patens* (Fig. 2) to a lower elevation marsh dominated by *Spartina alterniflora* that is more frequently flooded, with more open water and marsh edge (Fig. 3). This trajectory of geomorphic change is conceptualized as driven by the direct impact of three external drivers (sea-level rise [SLR], climate change, and human activities in the watershed) but highly modified by internal feedbacks. PIE is an excellent system in which to gain an understanding of the mechanisms of geomorphic change and how they will interact with ecosystem structure and function. Cross-system comparisons with other LTERs along gradients of temperature, species composition, tidal range, and sediment supply will further

Fig. 3. Schematic representation of hypothesized geomorphic changes in PIE marshes, from the Past *S. patens* - dominated high marsh , through the Present transitional state, to the Future *S. alterniflora*-dominated low marsh.

our mechanistic understanding of long-term change in coastal ecosystems.

Our proposed research is designed to **increase understanding of how the structure of the estuarine-marsh ecosystem will change over time and to understand what consequences these changes will have on ecosystem function.** Our research focuses on the dynamics and interactions between the geomorphology, biogeochemistry and ecological structure and function of the Plum Island marsh-estuary, in response to the external drivers. These drivers, their direct impacts, and key interactions are conceptualized in (Fig. 4.) We are carrying out our research at a mechanistic level so that our findings will be applicable to other systems where the relative strengths of drivers may differ.

In our conceptual model (Fig. 4) the watershed is part of the coastal ecosystem. We will examine not only the impact of water, sediments, organic carbon and nutrients outputs from the watershed on the marsh and estuary, but also processes *within* the watersheds that influence these outputs. We view geomorphology as the physical structure of the marsh-estuary system, including the relative ratios of frequently

Fig. 4. The overall conceptual model for PIE IV showing the three external drivers, acting directly on the marsh and estuary and through changes in material fluxes from the watershed. The response of the marsh-estuarine system is modified by interactions within the system which either dampen or magnify the effect of the external drivers. Our three questions examine how external drivers and internal feedbacks will modify: 1) Geomorphology 2) Biogeochemistry and Primary Production and 3) Consumer Dynamics and Food Webs.

flooded low marsh to infrequently flooded high marsh, creek bank length (edge), the ratio of marsh to open water, and the area of ponding on the marsh platform. For coastal ecosystems, rising sea level is a major restructuring driver. As sea level rises, sediment supply from the watershed, as well as feedbacks between the biogeochemistry and the vegetation will influence geomorphic change and help stabilize marsh and estuarine configurations. In turn, changes in the geomorphic configuration will have major impacts on consumers, trophodynamics, and biogeochemistry within the coastal ecosystem. Below we present our three major research questions with brief justifications. We then present the results of prior research (Section II) for additional context before describing the Proposed Research in detail (Section III).

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?

Sea-level rise (SLR) is a major driver of change in coastal ecosystems. Tidal marsh elevation must keep up with rising sea level through a combination of the burial of organic matter produced *in situ*, and the trapping of suspended sediments or marshes will convert to tidal flats and open water. Watersheds historically have been important sources of sediments to marshes, but their importance has decreased with the proliferation of dams and other flow restrictions (Weston 2014). The elevation of the marsh platform relative to sea level, tidal amplitude, and external sediment supply regulate marsh accretion through a complex set of feedbacks governed by the productivity of marsh vegetation (Morris et al. 2002; Morris 2005; Kirwan and Murray 2007; Kirwan et al. 2010). Therefore, although sediment supply is a major factor determining the maximum vertical accretion potential in many wetlands, (Kirwan and Murray 2007; Day et al. 2011; Mudd 2011; Fagherazzi et al. 2012), understanding the feedbacks between sediments, vegetation, and sea level is critical to predict the ability of marshes to keep pace with SLR.

Marshes must also contend with lateral erosion from wind driven waves and tidal currents (Leonardi et al. 2015). The erosion of marsh edge, followed by deposition of eroded sediments on the marsh platform (marsh cannibalization), can be important source of internally generated sediments that may greatly slow the rate of marsh loss. An open question is whether marsh cannibalization or the
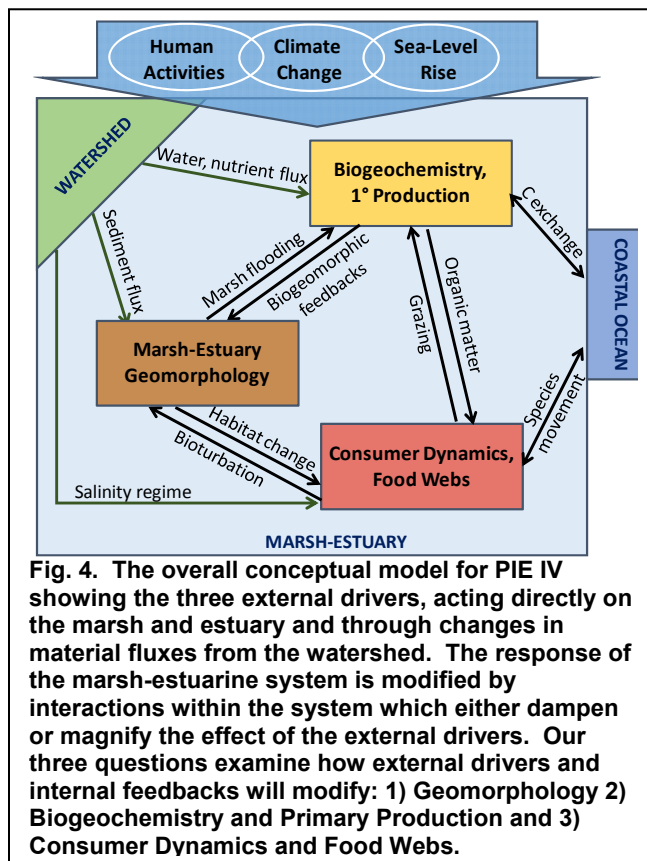
feedbacks between sediment supply and vegetation can overcome the declines in watershed inputs of sediment. If not, we expect that marshes with low total suspended sediment, such as Plum Island, will be less resilient to increased rates of sea level rise resulting in loss of total marsh area and a conversion of high marsh to low marsh (Fig. 5, Kirwan et al. 2010; Fagherazzi et al. 2012).

To address this question, *we will examine how external drivers such as SLR drive erosion within the marsh and estuary, (Hypothesis H1.1 below), how potential changes in sediment dynamics in the watershed alter delivery of sediments to the estuary (H1.2), and how feedbacks between marsh vegetation, sediment supply, and SLR will reconfigure marsh and estuarine geomorphology (H1.3).*

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

At the global level, estuaries and ocean margins play a key role in the transport, transformation, storage, and exchange of water, organic matter, and nutrients between the land, sea, and air (McKee et al. 2003; Seitzinger and Harrison 2008; Battin et al. 2008: Bauer et al. 2013). Anticipated alterations in marsh
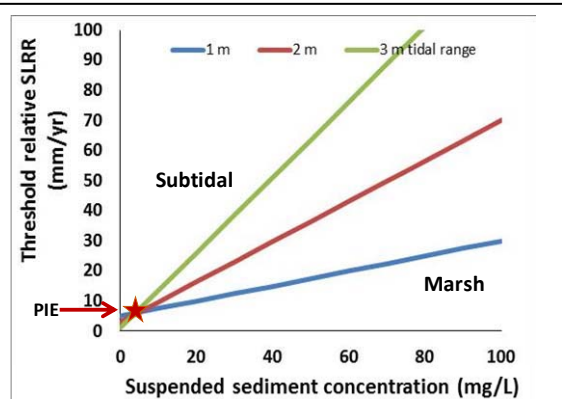
Fig. 5. Predicted threshold rates of sea-level rise for a variety of suspended sediment concentrations and tidal ranges above which intertidal wetlands will not persist. Nominal sediment concentrations in PIE are low but internal sources (marsh cannibalization) are not considered (Adapted from Kirwan et al. 2010).

geomorphology will result in a transition towards more low-elevation marsh areas (*addressed in Q1*) and may alter the rates of these important processes. In addition to alterations to marsh geomorphology, coastal systems will experience changes in other important drivers such as temperature and inputs of freshwater and nutrients that will accompany climate change and human activities in coastal watersheds. It remains unclear how coastal biogeochemistry and productivity will respond to changes in multiple drivers. Tidal marshes are very productive systems that store large amounts of carbon (C) (Morris et al. 2013, Hopkinson et al. 2012), and primary production in marshes is highly responsive to anomalies in sea level (Morris 2007; Morris et al. 2013). While loss of marsh area is expected to reduce coastal C storage, we cannot yet predict how production and C burial will change in the marshes that endure but experience modifications in flooding and changes in dominant plant species. Changes in marsh geomorphology will likely alter the cycling of nutrients in marshes through amplified flooding depth and duration, increases in tidal creek edge, which are 'hot-spots' of nutrient exchange, and altered tidal flushing through marsh soils. Further, alterations in the timing and magnitude of freshwater, nutrient, and organic matter delivery from the watershed to the coastal system may drive changes in marsh plant community structure and overall C and nitrogen (N) cycling.

Alterations to coastal ecosystem geomorphology and tidal marsh C and N cycling, together with climate change and human activities in watersheds, will influence estuarine water-column metabolism. The transition towards a more frequently flooded marsh with increasing marsh loss will alter the availability of nutrients and organic matter in the open-water aquatic system. Although rates of aquatic primary production in estuaries can be high, driven by both nutrient inputs from rivers and by internal inputs from the benthos (Weston et al. 2010) and marsh porewater (Vörösmarty and Loder 1994), estuaries are typically net heterotrophic (Hopkinson and Smith 2004). Production and respiration within the estuary is sensitive to watershed inputs of freshwater, organic matter, and nutrients, as these influence residence time, salinity, nutrient availability and metabolism (Tobias et al. 2003; Giblin et al. 2010). It is unclear how changing marsh morphology together with climate and land use change will alter estuarine metabolism. Increased connectivity between the estuary and the marsh accompanied by amplified marsh flooding will likely alter both estuarine production and respiration. *We will examine how patterns of marsh production and C storage will change with alterations to marsh morphology and other external drivers (H2.1), how climate change and alterations within the watershed will change the export of water and materials to the estuary (H2.2), and how C and N cycling within the estuarine water-column is*

affected by alterations to geomorphology and by the tighter coupling between the marsh and the estuary (H2.3).

Q3) How will key consumer dynamics and estuarine food webs be reshaped by changing environmental drivers, marsh/estuarine geomorphology and biogeochemistry?
　　As oceans warm and sea level rises, the communities and food webs of the salt marshes and open estuarine waters stand to be altered in two fundamental ways. First, shifts in the abundance and distribution of species, driven by changes in temperature, salinity, and species interactions, could have cascading effects through the entire food web. Second, shifts in geomorphic features such as changes in the relative areas of low versus high marsh habitat, length of creek edge, and flooding levels and changes in ecosystem productivity will reshape species spatial distributions, food web structure and interaction strengths (Keil et al. 2015; Rocha et al. 2015). In the next decades, we expect climate-driven introductions of new species as warm-water species colonize previously 'cool' regions (Polozanska et al. 2013). A key unknown in range-expansions is the ecological effect newly arrived species will have on an ecosystem (Sax et al. 2007). Coastal ecosystems are excellent model systems for testing fundamental ecological concepts because an array of species with different life histories uses a mosaic of habitats (open bay, low marsh, high marsh) with alternative energy-flow pathways (detritus or living plant matter as a basal resource) that can affect how consumers respond to change. Understanding how environmentally induced changes to species in a complex interaction network result in subsequent shifts in the abundance of key species, food web structure, and energy flow is a fundamental challenge in ecology (Dodds 2009, Olff et al. 2009, Loreau 2010).
　　Our LTER findings indicate the need for new studies to link organism responses to predicted spatial and temporal variations of habitats and species composition, and to better incorporate trophic interactions across the seascape. In the research proposed here, we focus on species and communities that significantly contribute to estuarine function (e.g., marsh and open bay invertebrate and nekton communities, omnivorous species and mobile consumers) and that our work has shown are responsive to the expected environmental changes. We will continue our core long-term, spatially-explicit monitoring of marsh and open bay benthic invertebrate, zooplankton and fish communities, and isotopic surveys of functional groups to understand changes in organic matter source, trophic position and niche width and energy flow over time. *We will add new experimental work on mechanisms by which marsh configuration influences food webs and their function (H3.1). We will begin new work assessing the impacts of range expansion species (fiddler crab) via field experiments and food web modeling (H3.2). We will use Bayesian modeling of network topologies of feeding interactions to evaluate strong versus weak interactions in food webs and predict relative abundance change (H3.3). We will compare food web topologies to isotopic community and food web evaluations to determine how changing environment conditions and species composition will alter estuarine food webs (H3.3).*

II. RESULTS OF PRIOR (top 10 publications are in bold here and in the references)
PIE III has produced 169 total publications, including 119 in peer-reviewed journals, 7 PhD dissertations and 19 Master's theses. Since 1998, a total of 411 publications have acknowledged the PIE LTER.

Changing water and sediment inputs from the watershed - During the spring and late fall, river discharge controls estuarine salinity, material inputs and water residence time. During the summer and winter, internal processes increase in importance and connections between the marsh and the estuary dominate. We have evaluated how the role of the watershed will change with climate change and alterations of land use, including water use, in the watershed (Wollheim et al. 2013). To understand how changes in land use impact water and material exports from the watersheds, we have completed very high resolution mapping (0.5m) of key terrestrial patches and socio-ecological processes, focusing on urban infrastructure, land cover (imperviousness, lawns) and water management (e.g. water-use restrictions, withdrawals) (Harris et al. 2012a,b; Polsky et al. 2012; Giner et al. 2013; Runfola et al. 2013). Recent work incorporating these processes indicates that human activities are an important determinant of freshwater fluxes. Over the past 80 years, on average 20% of freshwater flows were diverted from the Ipswich watershed, with spikes as high as 60% during dry years (Wollheim et al. 2013). Net diversion occurs because of the unique arrangement of communities relative to water supply locations. Diversions have declined in recent years as socio-ecological feedbacks have reduced water use. Wollheim et al.

(2013) proposed a conceptual model of how ecosystem services provided by urbanizing watersheds evolve over time due to such feedbacks, which was further expanded on by Kaushal et al. (2014, 2015).

Nitrogen input from the watershed – There is intense interest in understanding the controls on N export from watersheds, and how it changes with development. We clearly established that the Ipswich and Parker watersheds export a lower percentage of N inputs than most northeastern watersheds (Wollheim et al. 2013). Between 1993 and 2010, >80% of total annual N loading was retained in all years, and increased to >90% in dry years. We used long term monitoring data, experiments and models to understand why PIE watersheds have extremely low rates of N export despite extensive and increasing suburban development with high N inputs (**Morse and Wollheim 2014**). Part of the reason for high N retention is that in contrast to most other coastal watersheds, our N sources are located far upstream which allows the river network to remove N during downstream transport (Mineau et al. 2015). In addition, abundant riverine wetlands in this shallow sloped watershed have the ability to buffer increased N loading, a role that may be increasing due to expanded beaver ponding since 2000.   Riverine wetlands are more effective at removing nitrate than channelized streams (Wollheim et al. 2014).   Recently, we focused specifically on biogeochemical processes in beaver ponds and reservoirs. While beaver ponds always result in greater residence time, they do not always result in higher N removal rates, indicating other factors may also be important (Whitney et al. 2015; Smith et al. 2013). Modeling studies support the concept that transient storage characteristics are an important control on N exports (Stewart et al. 2011) and that increasing wetland abundance explains the lack of increased N export despite greater development.

Uncertainty in using mapped data - Maps are universally used to evaluate temporal and spatial changes in landscapes. **Pontius and Millones (2011)** have developed a novel method to compare two maps that show a single categorical variable, such as land cover. The method is useful for both change assessment (analyzing transitions among categories over time) and accuracy assessment (comparing test data to reference information). For example, land change simulation models may produce various maps of forest versus non-forest, which can then be compared to a reference map of forest versus non-forest. Quantity disagreement answers the question of whether the simulation map has more or less forest than the reference map. Allocation disagreement compares the spatial configuration of the simulated forest to the reference forest. The two new metrics of quantity disagreement and allocation disagreement replace the traditional Kappa indices of agreement, which have been the default metrics for decades in many scientific fields, especially remote sensing and land change science. It is particularly important to distinguish between quantity disagreement and allocation disagreement when comparing a map from a simulation model viz-a-viz a reference map (Pontius et al. 2008).

Geomorphic changes in the estuary - A great deal of our work has been oriented around understanding the controls on relative marsh elevation. The change in marsh elevation is highly dependent on interactions among factors, such as sediment and nutrient supply, and changes in hydrology and temperature, which collectively determine productivity, vegetative composition and sediment capture (Morris 2002). Our research is guided by a theoretical model, the Marsh Equilibrium Model (MEM) (Morris et al. 2002; Morris et al. 2012; **Morris et al. 2013**). One goal of our research is to determine the value of sea-level rise beyond which the marsh cannot keep up. A synthesis of data from PIE and many other locations has shown that *in situ* organic accretion from the vegetation can only keep up with SLR up to a rate of about 3mm y^{-1} (Morris et al. 2016), which indicates that supply of external sediments is critical for marsh survival at high SLR rates. Another important factor in marsh survival is marsh erosion. Leonardi and Fagherazzi (2014, 2015) have measured deterioration of marsh boundaries at Plum Island for seven years and found it is a complex phenomenon, controlled by geotechnical and biological heterogeneities affecting resistance to erosion. We have used data from PIE and elsewhere to develop a better understanding of how storms lead to marsh erosion and how changes in storminess might alter marsh fate. Surprisingly, we found no critical threshold in wave energy above which marsh erosion dramatically accelerates (**Leonardi et al. 2016**). Hurricanes were responsible for less than 1% of marsh erosion while storms occurring about every 2.5 months did the most damage.

Additional factors contributing to the fate of marshes are the formation and enlargement of ponds on the marsh surface, and an increase in the density of tidal creeks. Ponds are enlarging, which translates directly to substantial changes in total edge and marsh edge drainage (Wilson et al. 2014**)**. If

pond size reaches a critical dimension, irreversible marsh erosion occurs (Mariotti and Fagherazzi 2013a).

To measure marsh wide changes, we began a detailed spatial analysis of the change in areal extent and volume of marsh sediments/peat between mean sea level (the elevation at which intertidal marshes begin) and mean higher high water (MHHW; near maximum elevation of tidal marshes at PIE). GIS analysis of 2005 and 2011 LiDAR images confirms a loss of about 74,000 m^3 of marsh. This agrees with our other observations of lateral erosion of Plum Island Sound (Leonardi and Fagherazzi 2014; 2015) and marsh edge erosion and/or lengthening of 1st order tidal creeks (Wilson et al. 2014). We believe that a large fraction of sediments eroded from marsh edges is subsequently deposited on the marsh platform, helping the marsh to keep pace with sea level. We call this process marsh cannibalization.

Carbon metabolism along the watershed estuary continuum - The global coupled marsh-estuary system contributes half of the estimated 0.45 $PgCyr^{-1}$ net uptake of the coastal ocean but large uncertainties in this important flux remain (**Bauer et al. 2013**). For example, better understanding of the marsh C balance is an essential component for predicting C sequestration in marsh peat and for the ability of marshes to maintain elevation relative to SLR. In 2011, we began direct measures of net ecosystem exchange (NEE) of carbon dioxide (CO_2) using eddy covariance flux towers in the tidal marsh. We developed new methods that can be applied to wetland systems experiencing tidal inundation (Forbrich and Giblin 2015). We have found the marsh to be extremely autotrophic during the May to October growing season, with NEE averaging 291$gCm^{-2}y^{-1}$ uptake over 2012-2014 (Forbrich and Giblin 2015). However, the marsh is heterotrophic the remainder of the year reducing the uptake by about 50%. This estimate of NEE is still higher than our estimates of C burial using sediment cores, suggesting substantial C export to the adjacent tidal creeks. High creekbank drainage (Gardner and Gaines 2008), coupled with measurements of high porewater concentrations of dissolved organic carbon (DOC) and dissolved inorganic carbon (DIC) support the conclusion that there is a large lateral flux of carbon from the marsh to the estuary which exerts a strong control on estuarine metabolism (Vallino et al. 2005).

In contrast to marsh-derived C, terrestrial C only influences estuarine processes in the upper estuary, although much of it remains unused (Hopkinson and Vallino 1995; Vallino et al. 2005). To determine if extensive watershed processing is occurring, leaving only refractory material for export to the estuary, we conducted research to quantify the fate of terrestrial DOC within the river system (Wollheim et al. 2015). Using a unique combination of spatially distributed sampling of three DOC fractions throughout the river network and modeling, we found that aquatic reactivity of terrestrial DOC is low, suggesting that river systems may have only a modest ability to alter the amounts of terrestrial DOC delivered to coastal zones (Wollheim et al. 2015).

Nitrogen metabolism in the estuary and marsh - Salt marshes and estuaries are extremely productive ecosystems with high rates of nitrogen assimilation. Our research has examined the relative importance of processes that remove nitrogen (denitrification and anammox) versus a competing nitrate reduction process, dissimilatory nitrate reduction to ammonium (DNRA), that conserves nitrogen (N) within the ecosystem. Our research has shown that anammox is relatively unimportant in marshes (Koop-Jakobsen and Giblin 2009) while DNRA is a major nitrogen pathway that cannot be ignored. In a cross-site comparison of the importance of denitrification vs. DNRA in 55 coastal sites we found that DNRA accounted for more than 30% of the nitrate reduction at 26 sites (**Giblin et al. 2013**), with important implications for estuarine production. DNRA also appears to be especially important in the rhizosphere of marsh plants (Koop-Jakobsen and Giblin 2010) and this N conserving mechanism may enhance marsh production. In sediments, both DNRA and sediment ammonium adsorption vary with salinity (Weston et al. 2010). During summer, as salinity rises, ammonium is released from sediment particles and DNRA dominates over denitrification. This large sediment ammonium flux supports a mid-summer oligohaline phytoplankton bloom at a time when N inputs from the watershed are near zero due to low discharge. Salinity appears to also mediate nitrate reduction process by altering rates of nitrate production by ammonium oxidizing bacteria (AOB) (Bernhard et al. 2007). Surprisingly, although ammonium oxidizing archaea are more abundant than AOB and similarly structured by salinity they were not strongly correlated with nitrification rates suggesting they may be also using alternative energy sources (**Bernhard et al. 2010**).

To test the impact of increased nitrate in coastal waters on nitrogen cycling processes, nitrate has been experimentally added to tidal creeks for 12 years through a separately funded experiment (TIDE).

Increased nitrate availability stimulated both denitrification and DNRA in tidal creek sediments (Koop-Jakobsen and Giblin 2010; Vieillard and Fulweiler 2012) and on the vegetated platform although rates in the subsurface rhizosphere on high marsh were not enhanced (Koop-Jakobsen and Giblin 2010). Whole system mass balance calculations pointed to the creek edge as the hotspot for denitrification and preliminary whole system creek measurement of N_2/Ar to assess denitrification support this conclusion. Our understanding of N cycling processes is being enhanced by the analysis of microbial community composition in enriched areas (Bowen et al. 2011, Graves et al. in press). New work is suggesting that N inputs significantly alter the microbial community in unexpected ways. Kearns et al. (in review) found the highest reported rates of microbial dormancy in nutrient enriched salt marsh sediments. Nutrient enrichment also led to a dramatic loss of diversity among the overall active bacteria while promoting the success of a small number of sulfate reducing bacterial taxa that are likely important in nitrogen cycling.

Modeling biogeochemistry - We have developed a new thermodynamic approach based on maximum entropy production (MEP) to understand and model microbial biogeochemistry (Vallino 2010; **Vallino and Algar 2016**) that is more robust to model extrapolation than conventional approaches we have used in the past (e.g., Vallino 2000). When applied to N cycling in anaerobic environments, the MEP model shows that DNRA should be the dominate N pathway under high organic carbon loading (Algar and Vallino 2014), which is consistent with our observations (**Giblin et al. 2013**). The model also shows that microbial communities are highly adapted to periodic inputs of energy (Vallino et al. 2014). Currently, we are implementing the MEP model in a 1D framework similar to our metabolism model (Vallino et al. 2005) to facilitate application to PIE and elsewhere. We also have recently implemented a "Darwin based model" which is computationally more efficient (see H2.3 below).

Key consumers and controls on food webs - Mummichog (*Fundulus heteroclitus*), grass shrimp (*Paleomonetes pugio*), Atlantic silversides (*Menidia menidia*), sand shrimp (*Crangon septemspinosa*) and striped bass (*Morone saxatilis*) are key species in our estuary, accounting for over 85% of the biomass of mobile consumers. These species are central nodes in both marsh and open bay food webs with a high number of links to other species, use multiple energy-flow pathways and exert top-down control (Fleeger et al. 2008; **Nelson et al. 2015**). They also respond to river flow and marsh flooding (Haas et al. 2009; Mather et al. 2009) and forage across habitat boundaries (Kennedy et al. 2016). We have shown that marshes provide trophic subsidies via mobile nekton to top predators in open bay food webs (Kennedy et al. 2016; Baker et al. 2016) consistent with the idea that trophic subsidies should flow from high to low productivity areas. Top-down control led to increased densities of marsh surface detritivorous snails when mummichogs were reduced, which may accelerate detrital decomposition and N cycling (Johnson et al. 2009). However, contrary to the trophic cascade hypothesis, experimental reductions of mummichogs did not increase algal biomass because a behavioral shift led to grass shrimp functionally replacing mummichog as a predator (Fleeger et al. 2008; Johnson and Fleeger 2009). Direct grazing of *Spartina* was minor (Johnson and Jessen 2008) and many omnivorous species (e.g., polychaetes, tanaids and harpacticoid copepods) fed on high quality algal resources rather than detritus (Galván et al. 2008; Fleeger et al. 2008; Johnson et al. 2009; Galván et al. 2011; Pascal et al. 2013, 2014). Feeding flexibility by omnivorous species confers food web resilience to changes in detrital biomass as expected in reticulate omnivorous food webs (Buchsbaum et al. 2009). Striped bass and birds that migrate long distances to use seasonally abundant food resources at PIE suggest biotic connections among Atlantic estuaries (Mather et al. 2013). However, bioenergetics calculations indicate Snowy and Great Egrets, while seasonally abundant foragers on the marsh, are not dominant enough to affect marsh invertebrate consumer abundance.

Southern species range expansions - Warming oceanic temperatures have made previously occasional southern species more regular members of the community (e.g., migratory top predator bluefish was abundant in 2014) and introduced novel species as ranges extend further north. In 2012 we documented the warm-water blue crab, *Callinectes sapidus*, (Johnson 2015) and in 2014 for the first time we found adult Atlantic marsh fiddler crabs, *Uca pugnax* (Johnson 2014). We hypothesize that higher than normal summer water temperatures in 2012/2013 (1.3^{o}C higher than the average of the previous decade) allowed for the northern expansion of warm-water crab species, while estuarine temperatures and circulation may allow persistence once established. Our 3D circulation model (PIE-FVCOM: Zhao et al.

2010), shows a strong clockwise residual circulation around PI Sound, which favors fiddler crab larval retention.

Spatial changes in food webs - We used spatially-explicit isotopic measurements of breadth of basal resources (δ^{13}C) and trophic position (δ^{15}N) in a "community module" approach to assess the spatial changes in food web drivers (**Nelson et al. 2015**). A community module is a small group of species that share an interaction network that can be used to examine how communities respond to change. The upper estuary food web had highly variable basal resource use related to freshwater input, which controls both the quantity of watershed organic matter inputs (Wollheim et al. 2015) and phytoplankton blooms in the upper estuary (Weston et al. 2010). The middle estuary was more dependent on marsh, with the lower estuary dependent on more marine open water production. The trophic level of mummichog increased (from 2 to about 3.5) with longer high marsh access confirming the importance of the marsh habitat as a foraging location.

Geomorphic effects on food webs - We found migratory striped bass were consistently associated with salt marsh creeks, especially confluences with lots of edge area that connect salt marsh creek habitat with the open water habitat (Kennedy et al. 2016). Stable isotope and diet observation indicate that almost 50% of striped bass biomass in this region of the estuary is derived from the marsh (Baker et al. 2016). Our large-scale marsh nutrient enrichment experiment (TIDE) has shown declines in nekton, but not invertebrate, production in the last 4 years as N enriched marsh creek banks deteriorated and low marsh was lost (**Deegan et al. 2012**). This was in contrast to a bottom-up driven doubling of fish and invertebrate biomass in the first 7 years (Johnson 2011; Pascal et al. 2013; Mitwally and Fleeger 2013; Pascal and Fleeger 2013; Johnson and Short 2013).

Supplements - Supplements to the PIE LTER have benefited our program in several ways. First supplements allowed us to make critical improvements to our project boats and vehicles. Second, supplements were used to replace a variety of outdated and poorly working sensors used in the estuary and expand our continuous monitoring in anticipation of dam removals in the watershed. We purchased new sondes, an *in situ* fluorometer, conductivity and pressure sensors, and current meters to replace or augment older *in situ* monitoring instruments and replaced our GPS equipment with a much more accurate system. Finally, we used supplement funds to purchase instruments to expand our research capabilities. New acoustic receivers and better tags allowed us to track striped bass within PIE estuaries and determine which geomorphic features they preferred. A canopy analyzer allows us to track plant biomass over the season. We greatly enhanced our ability to monitor carbon fluxes within the estuary and to the ocean through the purchase of a new Apollo DIC analyzer and alkalinity titrator. A new SeapHOx, for continuously measuring pH, oxygen, salinity and temperature, was deployed at the southern entrance to Plum Island Sound allowing us become part of the ocean acidification network in the Gulf of Maine. We purchased several instruments needed for our eddy flux tower. Use of RET and RHS supplements are described below.

Education and Outreach - Nearly all of our education and outreach programs are on-going so they are only briefly described here (see Section III for more details). Our award winning K-12 schoolyard program, "Salt Marsh Science", serves over 1,000 students in grades 5-12 in ten schools. In 2011 PIE's education coordinator, Elizabeth Duff, received the prestigious "Massachusetts Marine Education of the Year" award for this project. In addition, local high school (HS) students also do internships at PIE and through RET and RHS supplements we had a local teacher work with 2 high school students studying striped bass. We are actively supporting the high school environmental stewardship programs run through the Gulf of Maine Institute. From 2010-2015 a total of 24 college undergraduate students funded through the NSF Research Experience for Undergraduates (REU) program have spent the summer in residence, 10 through funding to the LTER, and the rest by grants to our partnering universities. In addition to the REU program, 21 undergraduates have worked or conducted summer research at PIE and dozens of students have visited our site through class projects and field trips. Thirty-one graduate students have conducted their research under the auspices the PIE LTER Program from 2010-2015 and we have hosted 5 post-doctoral fellows. Other students and post-docs have used the facilities and field sites at PIE to conduct their own research.

Two new graduate activities took place during PIE III. 1) PIE scientists collaborated with scientists from the other east coast LTER sites to teach two on-line courses organized by Steve Pennings (GCE).

The first course was offered for credit at 9 universities and the second course was offered by 20 institutions. 2) The MBL-Brown IGERT program had three first-year classes focus on PIE as a site to learn how next generation gene sequencing techniques can be used to explore important and interesting ecological questions. The first class has published a manuscript (Graves et al. in press).

The science carried out at PIE has influenced environmental policy locally, regionally and nationally. Outreach activities involve nearly every member of the team. PIE scientists serve on numerous advisory committees for federal and state commissions and nonprofit environmental organizations. They also engage the general public through presentations, articles in newspapers and magazines, social media, and citizen science and we host journalists through the Logan Science Journalism program. All on-going activities are detailed in Section III.

PIE LTER Mid-Term Review - The PIE LTER project mid-term review contained many favorable comments about our program's strengths (e.g., biogeochemistry, marsh processes), but also suggested three areas where we could improve: 1) Food webs and consumer communities, 2) Watershed connection to estuarine dynamics, and 3) Modeling. We are responding to these suggestions as follows: 1) Food Webs: The review team noted that food webs and animal community ecology should be given higher priority in the renewal to ensure progress equivalent to other areas. They were also concerned about whether the scale of the measurements on consumers matched the scale of the questions we were asking on geomorphology. In order to expand the food web activity we have brought in Dr. Jarrett Byrnes (U. Mass-Boston) as a new PI. Dr. Byrnes' background is in quantifying the network topology of food webs and examining how those topological properties might contribute to the stability and resilience of food webs. Additionally, responding to concerns that the scale of the foodweb work might not be easily related to changes in geomorphology, we have developed a tractable, testable set of hypotheses on how geomorphic changes will impact communities and foodwebs. We have expanded our marsh sampling, preserving the core sites of our long-term monitoring but adding sites to address the newly defined questions on spatial configuration (Q3). We have also included James Nelson (ULL) as a new PI. Jarrett and Nelson will develop a novel analysis linking food web topology modeling with our long-term stable isotope analysis of food webs to address theoretical issues of energy pathways and food web resilience (Q3 H3.3). In order to focus LTER resources on the broad estuarine food web, we will seek outside funding and rely more on our Federal and State partners to build on the excellent progress we have made on striped bass and migratory birds. 2) Watersheds: The team expressed concerns about the connection between the watershed research and estuarine dynamics and the slow progress on understanding the effects of dam removal. Watersheds control estuarine water residence time, determine the salinity structure (and therefore plant and animal distributions) of the marsh and estuary, can be important sources of nutrients, and are sources of sediments that influence marsh development. Understanding watershed processes is essential. In this renewal we emphasize watershed processes that more clearly link to central marsh and estuarine dynamics. In particular, we have added emphasis to factors regulating sediment delivery to the estuary, something that had not been a previous focus. The dam removal work was delayed by the long, slow process of obtaining state and federal permits but will go forward this year. Pre-removal information has been collected over the past year, and we have everything in place for the dam removal in late summer 2016.   We have also been conducting input-output and ecosystem process measurements in beaver ponds over the past three years to understand their role in regulating material transfer to the estuary. 3) Modeling: The review team, while acknowledging the novelty and theoretical basis of the MEP modeling, expressed concerns about the applicability of this approach to all aspects of our work. We feel we are making very good progress in biogeochemical modeling using this approach (e.g. Algar and Vallino 2014) and interest in this approach is growing (Chapman et al. 2016; Vallino and Algar 2016). However, we realized that during the review, we may have underemphasized the degree to which modeling is integrated into our program. These models and their application to our research questions are better described in this proposal.

III PROPOSED RESEARCH

The overall goal of PIE IV is to **increase understanding of how the structure of the marsh-estuarine system will change in the future and understand what consequences these changes will have on ecosystem function.** Even under somewhat conservative projections of future sea-level rise, the long-term survival of marshes is in doubt. There are rates of sea-level rise beyond which marshes will quickly transition to open water and mud flats, especially for coastal systems with low sediment inputs.

On the other hand, human interventions, including dam removals or marsh sediment additions, might reverse expected outcomes and future sea-level rise predictions are extremely uncertain. Our research, combined with cross-system comparisons, will increase the mechanistic understanding of the ability of marshes to keep up with sea-level rise. We know that rapidly changing environmental drivers will lead to alterations in geomorphology, community structure, trophodynamics, primary production, and biogeochemical cycling in the coming decades. Many of the changes that occur while these systems are in transition will be profound. Research focused on responses of coastal ecosystems to environmental change will address both fundamental ecological questions as well as provide critical information for managing these systems.

We will focus on gaining a mechanistic understanding of how the external drivers and internal feed-backs operate to mediate these changes (Fig. 4). To address these questions, we plan a major expansion of research and monitoring efforts focused on understanding high-elevation and low-elevation marsh-estuary systems, using a space for time approach. These new efforts will complement continued long-term monitoring activities to address how the geomorphology of the marsh-estuarine system is responding to sea-level rise, climate change, and human activities in the watershed, and how those changes will influence production, biogeochemical cycling, and foods webs throughout the system.

Specific Questions, Hypotheses and Research Approach

Q1) How will the geomorphic configuration of the marsh and estuary be altered by external drivers, watershed responses, and internal feedbacks (Fig. 6)?
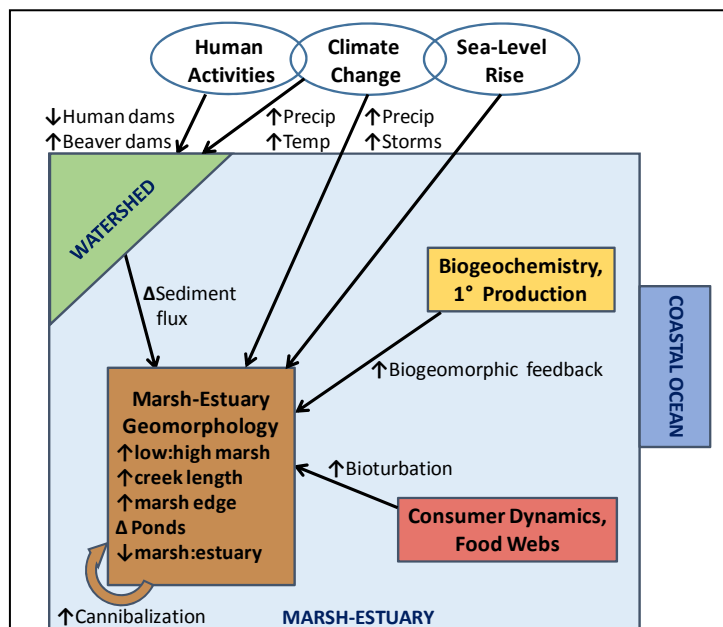

Fig. 6. Conceptual diagram for Q1. We will examine how external drivers lead to erosion within the marsh and estuary (H1.1), how changes in the watershed alter delivery of sediments to the estuary (H1.2), and how feedbacks between marsh vegetation, sediment supply, and SLR will reconfigure marsh- estuarine geomorphology (H1.3).

H 1.1) Sea-level rise and climate change will lead to an increase in the lateral erosion of marshes.
Rationale: Several processes lead to marsh erosion. As sea level rises there is an increase in the tidal prism (Fitzgerald et al. 2008), and this increase in water flow erodes tidal creeks, increasing their length and width (Hughes et al. 2009). Marsh boundaries are often eroded by wind waves (Leonardi and Fagherazzi 2014). This process is most important where marsh banks are next to areas of open water and increases with wind strength and water depth (Leonardi et al. 2016). The larger the body of water the greater the fetch and the greater the energy (Mariotti and Fagherazzi 2013a). Finally, waves undercutting creekbanks and ice rafting can break off pieces of marsh creek bank and transport them to new areas (Argow et al. 2011). All of these processes alter the current marsh configuration but because sediments are largely retained within the Plum Island estuary, the eroded sediments potentially provide a source of sediments for marsh accretion.

There have been a number of analyses of map/chart time series for selected areas of the PIE marsh and estuary to examine temporal changes in geomorphology (Priestas et al. 2012; Wilson et al. 2014; Quirk and Adamowicz 2016). We have analyzed LiDAR data from 2005 and 2011 to assess recent changes in elevation and marsh extent including losses from creek erosion (See Section II *Geomorphic changes*). The LiDAR data have also shown that there is little undeveloped upland available for marsh transgression. We now plan to perform a comprehensive analysis of historical changes for the entire marsh.

Approach:

Continued field studies: We will deploy current meters and wave gauges throughout the estuary for short-term campaigns as well as additional current meters for continuous operation in tidal creeks (see H1.3). The collected data will be used to determine the drivers of marsh boundary erosion and to calibrate and validate computer models of marsh evolution. There are a number of established survey points to quantify shoreline erosion and other changes in geomorphology of both the marsh and the creeks that are resurveyed annually.

New work: A new activity begun in 2015 is surveying the distribution of eroded marsh edge pieces (marsh turf, Fig. 7). Some of these turfs are becoming established at a lower elevation in the creekbed, and we hypothesize that they will expand over time, setting the stage for the transformation of high marsh habitat to low marsh habitat. Some appear to be already established on mudflats. The sites will be revisited annually, the presence/absence and size of each patch noted, and the presence of new turfs surveyed. We will conduct a life cycle analysis by measuring the birth and survivorship of turf in relation to elevation of the sediment surface and geomorphic orientation.

Fig. 7. A marsh turf in the Rowley River, August 2015. (photo K. Sundberg)

Modeling: *Hydrodynamics and sediments -* To determine the spatial distribution of tidal currents, waves, and related bottom shear stresses we will use the computational fluid dynamics package Delft3D (Lesser et al. 2004) coupled to the wave model SWAN (Booij et al. 1999). To assess the long-term evolution of the coastal landscape we will use the model Delft3D in conjunction with long-term hydrogeomorphic models already available (Mariotti and Fagherazzi 2013a,b,c; Mariotti et al. 2010; Mariotti and Fagherazzi 2010; Fagherazzi and Wiberg 2009; D'Alpaos et al. 2005; D'Alpaos et al. 2006). Our ultimate goal is to develop a detailed sediment budget for Plum Island Sound, thus determining the long-term fate of salt marshes and tidal flats. The long-term simulations will take into account future scenarios of sea-level rise indicated by the IPCC and Kopp et al. (2014), which includes local measurements of subsidence (Najjar et al. 2000) as well as dynamic adjustment of the sea surface and variations of the gravity field produced by mass redistribution (Salinger 2012).

Erosion of tidal flats will be determined by simulating wave and current bottom shear stresses as well as sediment resuspension with the model Delft3D-SWAN forced with storms (see Mariotti et al. 2010) (Fig. 8). We will thus quantify the total remobilization of sediments for each storm, and what fraction of it is exported to deeper waters or deposited on the mash platform. Simulated salt marsh accretion rates will be compared to the long-term data. Wind direction and wave energy will also allow us to determine potential erosion of marsh boundaries, utilizing 7 years of marsh retreat rates already measured (Leonardi and Fagherazzi 2015) and data from the retrospective analysis (see below). We will determine whether Plum Island Sound is experiencing a morphological change already noticed in other coastal lagoons, characterized by erosion of salt marshes boundaries, a deepening of the tidal flats and the silting of tidal-flat channels (Fagherazzi et al. 2006; Defina et al. 2007). We will also determine how the evolution of the coastal landscape will affect the Sound hydrodynamics in the future, by running a set of simulations based on the results of the long-term hydrogeomorphic models. We will thus unravel the complex interactions between the morphodynamic evolution of bays and their hydrodynamics. In particular, we will be able to determine whether a positive feedback exists by which erosion leads to a bay morphology that favors higher waves and therefore more erosion in the future (see Mariotti and
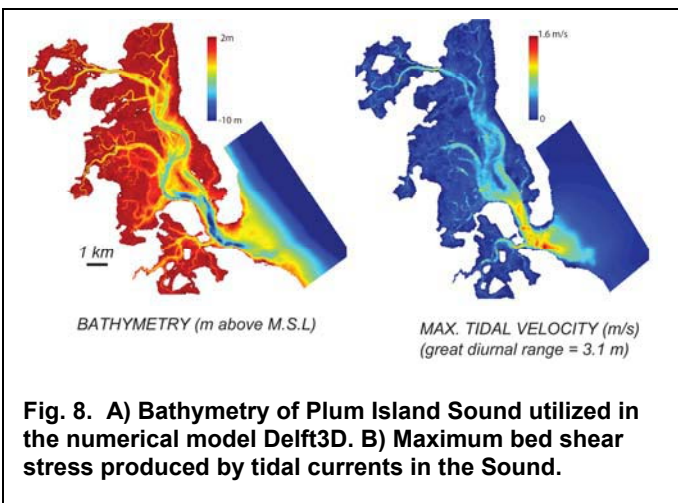

Fig. 8. A) Bathymetry of Plum Island Sound utilized in the numerical model Delft3D. B) Maximum bed shear stress produced by tidal currents in the Sound.

Fagherazzi 2013). If this is true, the system will evolve toward a less resilient configuration.
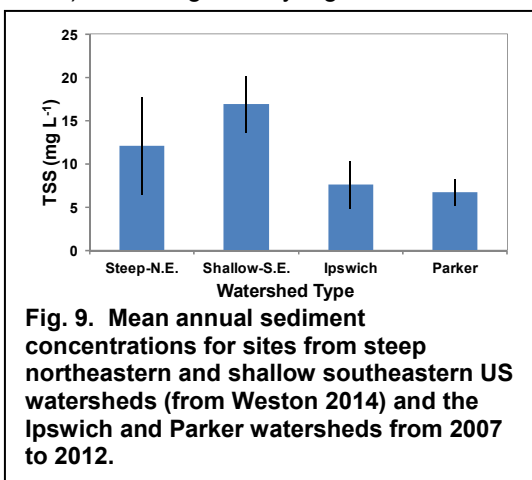*Retrospective analysis.* Characterization of the temporal change in the marsh requires more work concerning development of the database and methods of change quantification. We have carried out analysis of change for the whole marsh using recent LiDAR (2005-2011) and for specific areas using other data sources (e.g. Wilson et al. 2014). We have raw data for years 1888, 1938, 1952, 1971, 2011, and 2013 that have not been converted to GIS maps. We will use GIS to produce a consistent time series of georegistered maps for the categorical variable of land cover for these earlier years. As an endpoint to the analysis, we will collect new high resolution images.

We will build on our previous work concerning metric development to create new generally-applicable methods for change analysis. We developed a method known as Intensity Analysis to characterize temporal change for a categorical variable across multiple time points (Aldwaik and Pontius 2012, 2013; Huang et al. 2012). There are controversies concerning which aspects of Intensity Analysis are appropriate and how the results can be sensitive to the suspected errors and inconsistencies in the maps (Pontius et al. 2013). Thus we can use the PIE marsh example to develop Intensity Analysis further. One general theme concerns how to mathematically separate quantity change from allocation change. Quantity change considers the net change in size of each category. Allocation change considers the spatial distribution of change (Pontius and Millones 2011; Pontius and Santacruz 2014). Our previously developed methods allow us to measure the distances over which allocation change occurs, and we will continue to develop those methods (Pontius and Connors 2009). Conventional techniques to analyze transitions among categories use a Markov matrix, but it is not clear why marsh dynamics would follow a Markovian process. As an alternative, we have created a Flow matrix, which portrays each categorical transition as an area per unit time (Runfola and Pontius 2013). In our next phase of research, we will compare the properties of the Markov versus Flow matrices. All of these methods to analyze change are sensitive to the selection of the spatial extent. The challenge is a particular concern when analyzing change in a marsh because much of the change occurs on the edges between categories (Fig. 2). We will continue to develop generally-applicable methods to guide the selection of the spatial extent for situations when the changes occur on the edges of categories.

We will analyze changes of features to determine how rates of change, and types of changes, have varied over time. We will also use previous conditions to serve as a basis for testing model runs. For example, we will use Delft3D to take 'snapshots' at various times using old bathymetries to see what the forcing was at those times. Based on that forcing, we can extrapolate erosion rates and morphological trajectories and see how those extrapolations compare to data at other time points.

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.
Rationale: Despite urbanization, which tends to increase sediment loading, total suspended sediment (TSS) export from the PIE watersheds is among the lowest along the east coast of the US (Fig. 9; Weston 2014). TSS is generally higher in headwater streams across all land uses compared to the basin mouths, strongly suggesting TSS retention within the river system. High retention is likely due to the relatively shallow slopes of PIE watersheds, compounded by a series of reservoirs along the river main stem and abundant beaver ponds throughout the river network. Sediment concentrations and fluxes are a strong function of discharge, but the relationship varies depending on watershed characteristics (Richards 1982). Extreme precipitation coupled with expanding impervious surfaces will lead to greater sediment loads and sediment transport (Doyle et al. 2005, Raymond et al. 2016). Further, extreme events are more likely to cause beaver dams to fail, releasing pulses of sediments.

Fig. 9. Mean annual sediment concentrations for sites from steep northeastern and shallow southeastern US watersheds (from Weston 2014) and the Ipswich and Parker watersheds from 2007 to 2012.

Dam removals are accelerating nationwide in order to restore anadromous fish runs and sediment flows to marshes. More long-term studies of the consequences of these removals are needed (O'Connor et al. 2015). One of three dams in the Ipswich River watershed (South Middleton) will be removed in 2016, and removal of the Ipswich Mill Dam is in initial planning

13

stages. These dam removals are expected to lead to sediment mobilization, and reduced watershed sediment retention. The South Middleton dam is 30km upstream of the estuary while the Ipswich Mill Dam is at the head of tide. It is important to evaluate how spatial location of dam removal influences watershed scale sediment retention and exports (Doyle et al. 2003). However, the impact of human dam removal on watershed sediment export may be tempered by expanding beaver dams. Beaver have expanded considerably since 2000, and their dams may retain sediments, especially at low flow. In this round we will examine how ongoing land change, the removal of human dams and presence of beaver dams interact with variable climate to affect sediment exports.

Approach:
We will continue to quantify the magnitude, variability, and trends in fluxes of total suspended sediments and associated particulate carbon and nitrogen (TSS, PC, PN), DOC, and dissolved inorganic nutrients (expanded upon in H2.2) from the watersheds to the estuary. We will enhance monitoring, especially of sediments at the basin mouths, across flow conditions to test the hypothesis concerning the impact of changing precipitation variability. We will also expand measurements that uncover mechanisms influencing loading in the watersheds (land use-climate interactions), and retention during downstream transport (beaver ponds, human reservoirs). Loading and retention mechanisms are spatially and temporally dynamic. A new TSS module will be developed for our existing river network model, FrAMES (Wollheim et al. 2008; Stewart et al. 2011; Wollheim et al. 2015; Mineau et al. 2015). The new TSS module will integrate varying sediment sources, transport, settling, resuspension, and export over time and space, and will be used to test the effects of land use change, climate variability, human infrastructure, and beaver activity on TSS flux to the estuary.

Enhanced Long term monitoring for sediments. As part of our long term monitoring, we have measured dissolved nutrient concentrations with monthly sampling since 1994, and deployed autosamplers for high frequency sampling (daily) since 2001. We have estimated annual sediment fluxes using data from grab samples. Because sediment concentrations are highly dynamic during storms, which are infrequently sampled, this introduces considerable uncertainty (Allen and Castillo 2007). Our estimates of sediment fluxes will be greatly improved by high frequency*, in situ* measurements of turbidity, coupled with regular sampling and flow data, (Rasmussen et al. 2009), but will require heavy emphasis on storm sampling, especially in smaller, flashier systems, to develop robust surrogates (Anderson and Rounds 2010).   We will deploy continuous turbidity, colored dissolved organic matter (CDOM), conductivity, and water temperature sensors at the head of tide dams in the Ipswich and the Parker Rivers, conduct periodic intensive grab sampling during storms, and develop TSS/CDOM proxies to improve quantification of export fluxes (Rasmussen et al. 2009). These measurements will be used to identify the relative importance of base flow vs. storm flow vs. extreme events in the delivery of sediments and other materials from the watershed to the estuary (Doyle 2005).   We will also periodically target storm events in our long-term headwater sites (e.g. using autosamplers to measure TSS), as well as at the inflow and outflow of reservoirs and beaver ponds.

Dam removal experiments. We are currently determining the effect of reservoirs on ecosystem processes and net fluxes by taking advantage of the South Middelton dam removal scheduled for the summer of 2016. To capture pre-removal conditions, we are developing time series of retention for TSS, DOC, chloride (as a conservative tracer), and nutrients using input-output measurements. We have been studying 8 reservoirs in coastal New England (including three in PIE) to place this dam removal in context. We will continue these measurements during and following dam removal.

Sediment modeling. We previously developed a watershed modeling framework for water, C and N fluxes (FrAMES) (Wollheim et al. 2015, Mineau et al. 2015). In this LTER renewal, we will focus on developing a sediment module in FrAMES to understand how sediment fluxes to the estuary have changed historically, and how they are projected to change with ongoing watershed and climate change. The sediment module will account for effects of climate and land use on sediment loading to the river network, and retention processes during transport. Measurements from reservoirs and beaver ponds described above will be used to calibrate the model. FrAMES will be updated with the Modified Universal Soil Loss Equation (MUSLE, Williams et al. 1995) to simulate space and time varying fluxes throughout the network and export to the estuary. Loading of sediment to the aquatic system is driven by MUSLE, and is a function of daily runoff, peak discharge rate and factors that account for soil erodibility, cover, management, topography, and soil characteristics. Sediment transport through the channel network is a function of flow velocity, erodibility factor and channel bottom cover factor (Bagnold 1977; Williams 1980; Neitsch et al. 2011; Yesuf et al. 2015). Trapping efficiency by beaver ponds, reservoirs and lakes within
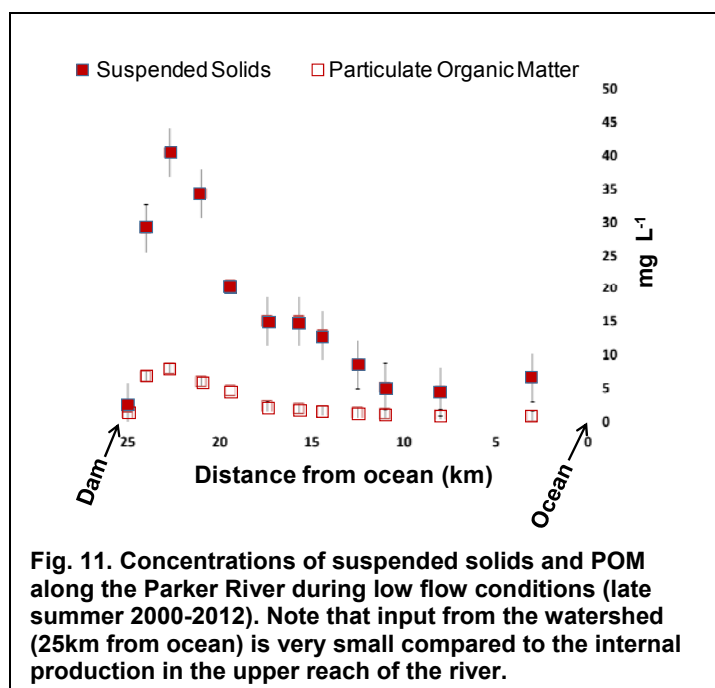
the river network will be estimated as a function of residence time (Brune 1953; Vorosmarty et al. 2003). Surface areas and volumes of reservoirs will be derived from available data sources while those for beaver ponds will be based on sampling a subset of ponds, related to available LiDAR and imagery.

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

Rationale: The measurements we make in H1.1 and H1.2 are designed to provide information on erosional forces altering the marsh-estuary configuration and changes in the supply of sediments from the watershed and marsh cannibalization. In H1.3, we will use this information together with measurements of the biogeomorphic feedbacks between vegetation on the marsh platform, sediment supply, and SLR to better understand long-term changes in geomorphology. Ponding on the high marsh at PIE suggests that the dominant high marsh plant, *S. patens,* may not be keeping up with SLR. Wilson et al. (2014) suggested this ponding may be cyclical. However, our most recent analysis of sediment erosion tables (SETs) suggests that while the high marsh was keeping up

Fig. 10. Accretion rates differ with elevation and vegetation type based on long-term SET records. All accretion rates can match the long term trend in sea level rise (2.8 mm y^{-1}). Under current (accelerated) sea level rise (4 mm y^{-1}), most high marsh sites accrete too slowly to maintain their position.

with previous rates of SLR, it may now be falling behind as SLR accelerates. In contrast, low marsh *S. alterniflora* currently benefits from increased inundation and sediments are gaining elevation at rates greater to or equal to sea level rise (Fig. 10). Increasing elevation in both vegetation types is attributable to two processes. First, a fraction of the *in situ* production, accumulates in marsh soils. Several lines of evidence suggest that the limit for this accretion is about 3 mm y^{-1} (Morris et al. 2016). The second mechanism for increasing marsh elevation is trapping of sediments from the water-column during marsh inundation.
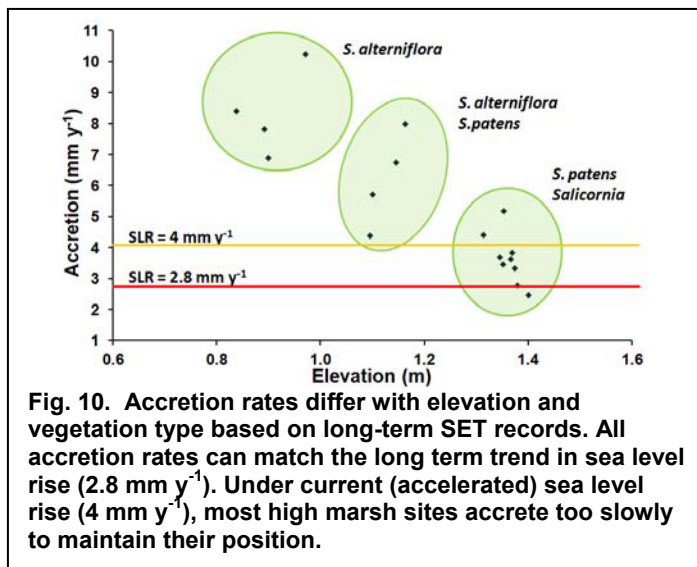
The response of marsh grasses to changes in sea-level, and interactions between the grass biomass and sediment supply are critical factors determining marsh elevation, and ultimately marsh loss or expansion. If sediments are available, increasing inundation as sea level rises leads to higher rates of sediment deposition, which helps tidal wetlands keep up with SLR, simply because longer inundation times allow more sediment to drop out of the water column (Pethick 1981; Krone 1985) facilitated by flow reductions in the plant canopy (Lima et al. 2015). Vegetation growth itself in tidal wetlands is highly responsive to variations in inundation. In salt marshes, vegetation growth has an optimal elevation. If the marsh surface is above the optimum, more flooding from SLR will increase plant biomass, potentially enhancing sediment trapping and organic matter accretion, and limiting erosion (Morris et al. 2002; Morris et al. 2013). These types of biogeomorphic feedbacks likely explain the development of wetlands within the intertidal zone over

Fig. 11. Concentrations of suspended solids and POM along the Parker River during low flow conditions (late summer 2000-2012). Note that input from the watershed (25km from ocean) is very small compared to the internal production in the upper reach of the river.

thousands of years (Redfield 1972). The long-term stability of coastal wetlands is therefore predicted to be a function of interactions among sea level, primary production, sediment supply, and sediment accretion, with the availability of sediments ultimately determining the maximum rate of vertical accretion in most wetlands. The source of these sediments may be the watershed (H1.2), or internally produced sediments from erosion of tidal flats and marsh boundaries (H1.1). Our data suggest that currently most of the sediments in this system are produced from internal cannibalization of the marsh itself. Support for the importance of cannibalization comes from conservative mixing models that show an internal production of ancient, ^{14}C-depleted particulate organic C along the length of the estuary (Cavatorta et al. 2003, Raymond and Hopkinson 2003), and from TSS measurements within the estuary that show a mid-estuarine maximum (Fig. 11). Marsh cannibalization can account for a significant fraction of vertical accretion, and this is in agreement with the finding that the average ^{14}C age of the organic fines in the top 5 cm of peat is 1800 years.

Approach:

Long-term monitoring. – We maintain a NOAA quality tide gauge (established in 2011) to accurately assess local sea level. To assess accretion rates, we will continue long-term monitoring of our 18 SETs as well as marker horizons. These SETs are in different vegetation types and elevations. This data will soon be supplemented by more than 25 new SETs installed by the U.S. Fish and Wildlife Service (USFWS). We will also continue or long-term measurements of estuarine TSS along the main channels. Accretion rates throughout the Plum Island marshes are also being assessed using radiometric dating.

New activities: To focus on understanding the responses expected during the transition from high marsh to low marsh throughout the PIE system (Fig. 3) we will use a space-for-time approach (Picket 1989). In this approach, we will take advantage of existing areas of low marsh dominated by *S. alterniflora* along the Rowley River, together with adjacent areas of high *S. patens* marshes. We will monitor tidal creeks and associated creeksheds that drain either predominately high-elevation (n=3) or low-elevation (n=3) marsh (Fig. 12). These efforts will 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).

Sediment dynamics: To evaluate the dynamics of sediment retention and export in marshes of the Plum Island system, we will use the six tidal creeks described above. Transects across the mouth of the six tidal creeks (Fig. site) will be established for manual measurements of tidal water flow and TSS (*along with other measures – see H2.1, H2.3 below*) for six full tidal cycles per year (during neap and spring tides in the spring, summer, and fall). The tidal creeks will also be instrumented with current profilers, probes that monitor optical turbidity, conductivity, temperature, and dissolved oxygen, and autosamplers for discrete TSS collection. The manual tidal flow cross-sectional measurements and discrete TSS samples from occupations and automated
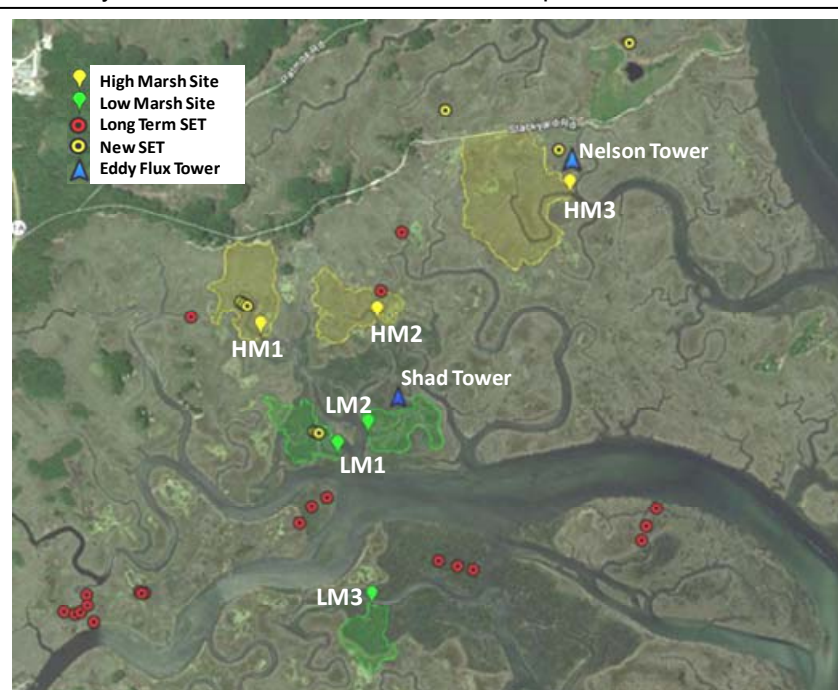

Fig. 12. Map of paired high marsh and low marsh creeksheds along the Rowley River (described in H1.3, H2.1, H2.3) with locations of SETs and flux towers.

samplers will allow for the parameterization of higher frequency TSS estimates derived from the current profilers and turbidity probes. The organic and mineral content of discrete TSS samples will be determined. We will use radionuclides to evaluate the characteristics of the TSS entering and exiting the 6 creeksheds to calculate the net import or export of sediment from tidal creeks draining marshes with varying geomorphology (Ganju et al. 2015). Water entering and leaving tidal creeks will be collected several times during each sampling event for measurement of particle-reactive Be-7 (λ = 53.2 d) and Pb-210 (λ = 22.2y) activities on TSS. The activities of the TSS will be compared to surface marsh sediment collected in each creekshed, and to the atmospheric deposition collected by wet/dry precipitation collectors (Neubauer et al. 2002). The radionuclide signature of the TSS, along with the mineral:organic content, help determine the source of the sediment entering and exiting low versus high elevation marshes and the role of cannibalization in supporting the TSS supply. In addition to measurements of tidal mass exchange of sediments, we will employ spectral density analyses of high-temporal resolution TSS monitoring data to ascertain coherence of sediment transport with dominant tidal periods in the Plum Island region, and analyze TSS data against wind speed and direction to evaluate important drivers of TSS in the system (Ganju et al. 2015).

Experiments: The role of sediment supply in supporting marsh accretion and the biogeomorphic feedbacks between sediments, plants, and elevation will be tested explicitly through a project commencing in 2016 (Weston, Morris, Craft, and Neubauer; NSF DEB-1457442). Water flooding high and low elevation marsh plots in the Plum Island system will be amended with suspended sediment to achieve +25 mg L^{-1} TSS (approximately doubling the TSS concentrations) for three growing seasons. Marsh elevation and plant biomass will be monitored, allowing for refinement and parameterization of MEM for use in both *S. alterniflora* and *S. patens* marshes. Long-term accretion rates throughout the Plum Island marshes, along with eight other marsh systems along the East Coast, will be assessed using Pb-210 dating on sediment cores taken at a variety of elevations. Changes in mineral accretion over time will be evaluated against changes in land use and riverine sediment supply in each system.

Modeling: MEM was originally developed as a 0D model that simulates change in marsh surface elevation as a function of *in situ* biomass production and deposition of suspended sediment. MEM simulates the response of marsh vegetation to relative elevation, incorporating key feedbacks between the two. We will continue to further develop MEM (H2.1) and use it to explore biogeomorphic change.

MEM has been linked now with the hydrodynamic model ADCIRC (Hydro-MEM) (Alizad et al. 2016) to simulate hydrodynamics and the biogeomorphological feedbacks across an estuary. An advantage of using Hydro-MEM model is its ability to capture a two-dimensional field of tidal flow and hydroperiod within the intertidal zone. ADCIRC contains a robust wetting and drying algorithm that enables the swelling of tidal creeks and overtopping of channel banks (Medeiros and Hagen 2013). Implementation of this model allows for complex feedbacks that affect the hydrodynamics resulting in variability in average MHW and tide range across the estuarine landscape. This allows for a better spatial representation of water level and tide range, marsh productivity and the local marsh response to SLR, which in turn affect hydrodynamics.

Q2) How will marsh and estuarine primary production, organic matter storage, and nutrient cycling be altered by external drivers, watershed responses and internal feedbacks (Fig. 13)?
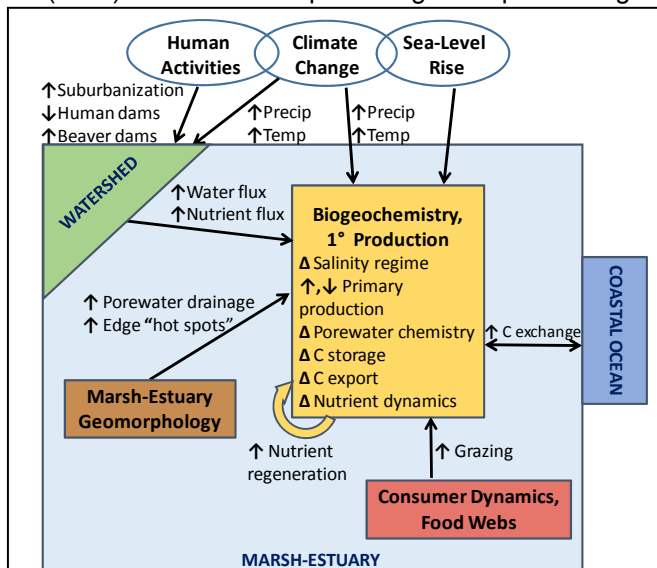

Fig. 13. Conceptual diagram for Q2. We will examine how marsh production and C storage will change with alterations to geomorphology and other external drivers (H2.1), how climate change and alterations within the watershed will change the export of water and materials to the estuary (H2.2), and how C and N cycling within the estuarine water-column change with alterations to geomorphology and tighter coupling between the marsh and the estuary (H2.3).

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.*
Rationale: Coastal ecosystems play a crucial role in ocean carbon storage (Bauer et al. 2013; Herrmann et al. 2015); and may be important to coastal DIC and alkalinity budgets.   Since global marsh extent has decreased and is projected to decline further with sea level rise, most studies suggest a loss of coastal C storage in the future (McLeod et al. 2011). Yet at present, we cannot say with certainty whether C storage in the remaining coastal marshes will increase or decrease. Net C uptake depends on a positive balance between marsh productivity and ecosystem respiration, which are both governed to different degrees by vegetation type, climatic drivers and sea level. Both net primary production and C burial in salt marshes is very high (Morris et al. 2013, Hopkinson et al. 2012), and measurements have shown that annual salt

marsh above ground primary production varies with anomalies in mean sea level (Morris 2007; Morris et al. 2013). The productivity of salt marsh grasses is highly influenced by porewater chemistry. While salt marsh halophytes have the capacity to oxidize their rhizosphere and remove salts, at some point this capacity becomes overwhelmed. Therefore, processes which decrease salinity, such as high rates of tidal flushing, which increase with tidal amplitude, or rainfall, may increase production. This is the major reason why *S. alterniflora* aboveground net productivity is correlated with hydroperiod (Morris et al. 2013), which integrates flooding duration and frequency. However, increased flushing may also increase decomposition by increasing sediment aeration and favoring oxic respiration and coupled nitrification/denitrification over less efficient sulfate reduction.
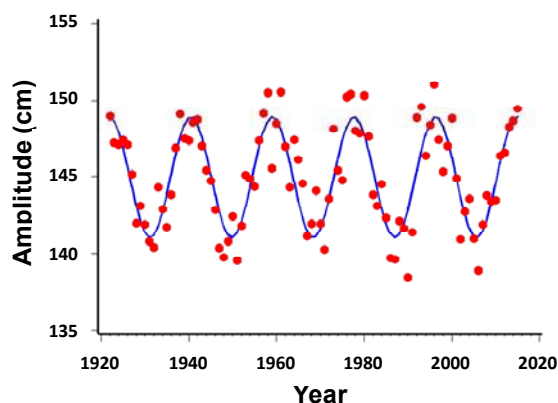

Fig. 14. Mean tidal amplitude (June – August) in Boston. Showing the 18.2 year solar-lunar nodal cycle (blue line is harmonic fit). Amplitudes were computed as (MHW-MLW)/2 (NOAA Boston tide gauge)

S. alterniflora production correlates positively with MHW, not MSL (Morris et al. 2013). While MHW certainly changes due to SLR, oscillation in the *amplitude* of the tidal range varies with the 18.2 year solar-lunar nodal cycle (Fig. 14). This means during the current rising phase of the nodal cycle, MHW increased by almost 10 cm over 9 years (Fig. 15), which is more than three times the MSL rise, leading to a change of nearly 14 cm over the same period. This major change in the flooding regime explains why adjustments in marsh surface elevation often lag interannual anomalies. This lag in the response of marsh elevation explains the interannual variations in annual primary productivity that Morris and Haskin (1990) and Morris (2000) have reported.   Data from PIE strongly support the importance of
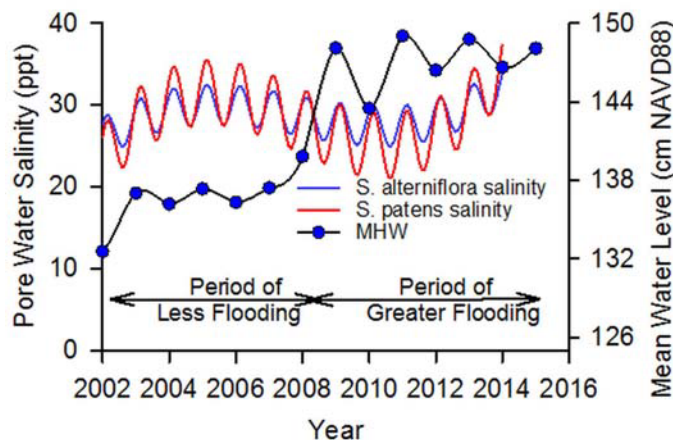

Fig.15. Summer MHW (NOAA Boston tide gauge) by year and the harmonics of mean porewater salinity from our long-term monitoring sites. The *S. alterniflora* site floods daily, which reduces the amplitude of its annual salinity cycle relative to the *S. patens* site, but a higher MHW at both sites means a greater duration of flooding and lower porewater salinities.

control of porewater salinity by MHW (Fig. 15). The *S. alterniflora* site floods daily, which reduces the amplitude of its annual salinity cycle relative to the *S. patens* site, but obviously a higher MHW at both sites means a greater duration of flooding and lower porewater salinities.

Determining the impact of these porewater changes on net C storage is difficult. While above ground production can be measured very accurately on an annual basis, it is more difficult to measure below ground production and impossible to measure small differences in annual rates of C storage using sediment data. Whole system eddy covariance measures show great promise in exploring the relationship between climate, SL and C storage. Examining growing season net ecosystem exchange (NEE) during years when sea level was similar, we observed that temperature is important but that the timing of the deviations from normal are equally important. For example, in 2012 during an exceptionally early and warm spring, net productivity was high, but this was later negated by high respiration during a warm fall (Forbrich and Giblin 2015). In addition, our continuous annual data sets of NEE patterns (Fig. 16) reflect the impact that warm periods in the non-growing season have on C losses due to respiration

Fig. 16. Cumulative NEE for a high marsh site for 2013-2015. During the non-growing season, the site acts as small but continuous CO$_2$ source (positive fluxes). During the growing season the marsh rapidly becomes a sink (negative fluxes). In all three years, the system is an overall C sink of varying strength depending on climatic drivers.

(winter 2013, fall 2015). Concurrent measurements of whole system NEE using eddy covariance, porewater measurements, measurements of above ground production and peak above and below ground biomass will help separate out the relative importance of climate and sea level on production and C storage.

Approach:

Current activities: We will continue to maintain two eddy covariance systems to measure ecosystem CO$_2$ exchange at a high marsh and a low marsh site (Fig. 12). Additional measurements include climate variables, water table height, and the phenology of grasses. The measured fluxes are partitioned to determine gross primary production and ecosystem respiration (Forbrich and Giblin 2015).

New activities: We will expand our activities to better describe biological and biogeochemical processes within each tower footprint. We will conduct spatially extensive biomass sampling in high and low marsh, which will give us a better understanding of the amount and distribution of leaf area within and between the two sites. We will also record porewater salinity to better analyze the effect of high salinity events on GPP. The C budget of the marsh determined by the eddy covariance method remains unconstrained due to horizontal fluxes of C during tidal exchange. This is less of an issue at our high marsh site but very important at our low marsh site. To fully constrain the marsh C budget and assess NEE, we will measure of horizontal C exchange in the tidal creeks draining high and low marsh as described below (H2.3).

Further development of the MEM model requires additional data collection. First, the growth curves of both *S. patens* and *S. alterniflora* need to be fully characterized. Using marsh organs (Fig. 17) we have been able to document the
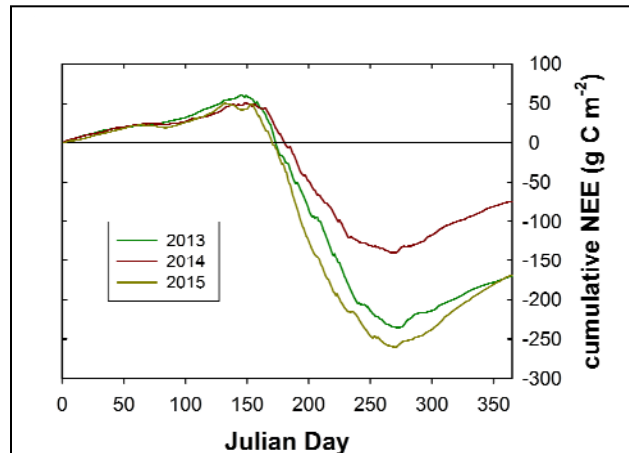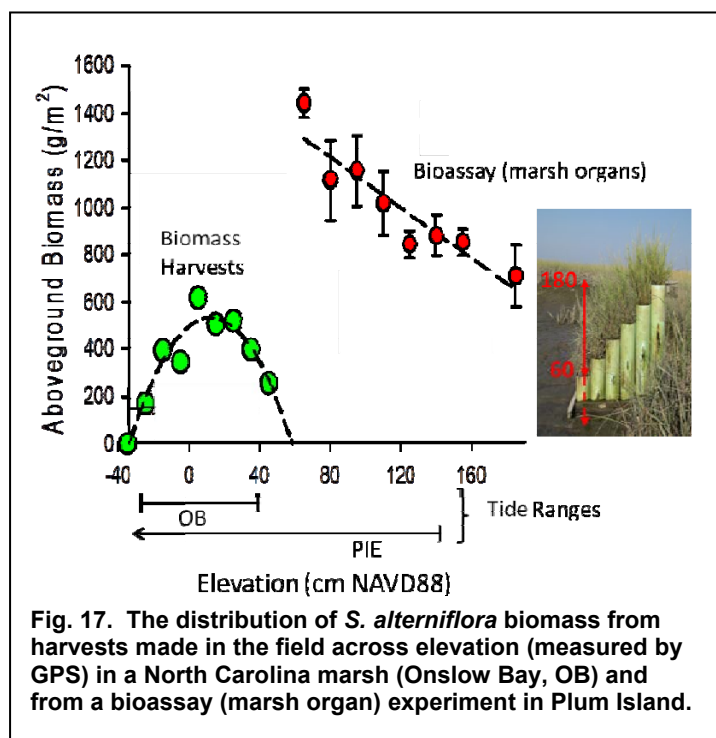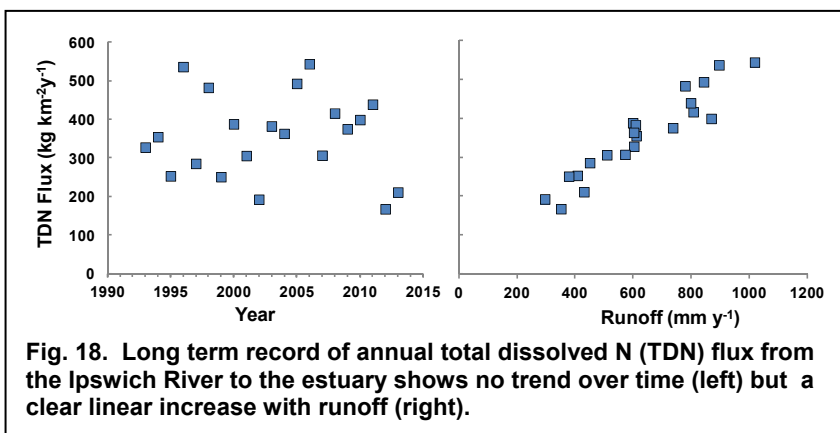

Fig. 17. The distribution of *S. alterniflora* biomass from harvests made in the field across elevation (measured by GPS) in a North Carolina marsh (Onslow Bay, OB) and from a bioassay (marsh organ) experiment in Plum Island.

19

response of *S. alterniflora* to changes in relative elevation at the highest portion of the tidal frame, but placement of the marsh organ at lower elevations is not possible at PIE due to the large tide range and the absence of a suitable location free of swift current and waves. Therefore, we plan to measure the growth curves of both species by collecting biomass samples in the field across each species' full spectrum of elevations measured using highly accurate GPS. This approach has been demonstrated successfully in a number of estuaries (Fig. 17). This sampling will be part of a larger effort to measure grass biomass where invertebrates are sampled (H3.1) and to characterize the tower footprints. Another important input to the MEM model is the distribution of root biomass and sediment organic matter concentration. We plan to measure root volume and biomass distribution over depth by scanning sediment cores using computerized tomography (CT; Davey et al. 2011). Cores for CT scans will be taken where we do the biomass harvests.
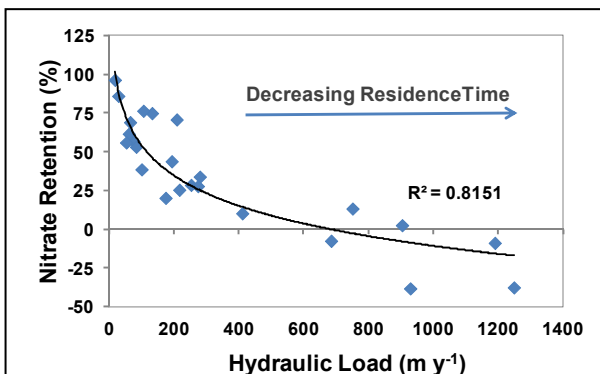
Modeling – We will expand our MEP biogeochemical modeling to the marsh platform (see H2.3). To better simulate the spatial patterns of biomass distribution at PIE in the Hydro-MEM application (H1.3), it is necessary to extend MEM to characterize *S. patens*.

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.

Fig. 18. Long term record of annual total dissolved N (TDN) flux from the Ipswich River to the estuary shows no trend over time (left) but a clear linear increase with runoff (right).

Rationale: PIE watersheds are experiencing increasing imperviousness with suburbanization and reduced net water withdrawals due to changes in water supply management (Wollheim et al. 2013). Combined with more extreme precipitation, the amount and variability of freshwater flows reaching the estuary is likely to increase. Watersheds retain more N in dry years than in wet years, evident at PIE and elsewhere (Kaushal et al. 2008).

Therefore, we expect that increased precipitation and runoff, combined with removal of human infrastructure (i.e. dams), will lead to reduced watershed scale N retention, and an increase in N exports. However, despite increased suburbanization and N loading to the watershed we have not seen a long-term increase in N exports (Morse and Wollheim 2014). In fact, two of the lowest annual N export years since measurements began in 1993 occurred in 2012 and 2013 (Fig. 18). We attribute higher N retention to the increase in beaver ponds. Therefore, if conditions become wetter, the response of N and potentially other solutes will be determined by how many beaver dams are present, and by their ability to remove N. Our measurements and models will elucidate the balance between these competing impacts.

Fig. 19. Nitrate retention estimated from input-output measurements from 8 reservoirs over three sample periods in MA and NH during 2015. Negative retention means the reservoir system is a net source. Hydraulic load is equivalent to mean depth / residence time, thus if depth increases, or residence time declines, hydraulic load increases.

Approach: We will monitor N forms and other solutes in all of the same places we are examining sediment fluxes as described in H1.2. This includes our long-term measurements in headwaters draining each dominant land use (urban, forest, wetland) and at the head of the tide dams, with enhanced sampling of storms at human and beaver dams.

Dam-removal experiments. In addition to sediment monitoring (H1.2) we have recently begun quantifying N retention rates in the reservoir behind the South

Middleton dam, scheduled for removal, using input-output measurements as well as experiments in which we add nitrate and a conservative tracer (Covino et al. 2010). We have also initiated measurements to better understand the mechanisms influencing net transformations by small reservoirs in a variety of locations (upstream, side pools, at outflow, downstream) (Fig. 19). Measurements include diel nitrate patterns using *in situ* nitrate sensors, ecosystem metabolism, trace gas emissions, and horizontal and vertical variability of temperature, dissolved oxygen, and nutrients. We will continue these "pre-removal" measurements through summer 2016 and then measure responses during and post removal. We will also conduct similar measurements in beaver ponds in the watersheds to evaluate their effect on fluxes and ecosystem processes relative to stream channels. We will use these measurements to develop a predictive understanding of net N and other solute transformations by dams in order to constrain model parameters to predict changing fluxes to the estuary.

Modeling. Modeling of water, N and C fluxes from the watersheds has been an integral research activity for the PIE LTER (Wollheim et al. 2015, Mineau et al. 2015). In this renewal, we will continue to build upon and use this model to analyze how changes in land use and management, including human dams and beaver dams, will impact water, N and C exports. To further enhance our N and C modeling we will integrate an aquatic metabolism model to link the N and C cycles (Sheehan et al. 2015), which we believe is necessary for understanding the current high watershed N retention and future changes. We will continue to capitalize on the high resolution land cover data that has been developed on previous LTER cycles to inform heterogeneity in nutrient, carbon and sediment loading.

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.

Rationale: Estuarine water columns are usually net heterotrophic (Hopkinson and Smith 2004; Herrmann et al. 2015), and our long-term monitoring indicates the Parker/Rowley River-Plum Island Sound system is typically heterotrophic as well (Fig. 20). Net heterotrophy is driven by organic carbon inputs from the watershed, surrounding wetlands, and the ocean. Rates of aquatic primary production can also be supported by nutrient inputs from the watershed, benthic recycling (Weston et al. 2010), and inputs from marsh porewater (Vörösmarty and Loder 1994). The importance of the various sources of nutrients and organic matter changes over space and time in the estuary. Further, C and nutrient cycling in the estuary, which are driven largely by freshwater inputs from the

Fig. 20. Rates of estuarine water-column respiration (R, top), gross primary production (GPP, middle), and net ecosystem production (NEP, bottom) as a function of conductivity (left) and temperature (right) in the middle portion of the estuary from over 10 years of monitoring.

watershed, interact strongly with water-column temperature, salinity, and residence time. Watershed nutrients and organic matter can drive primary production to high levels in estuaries resulting in large swings in metabolism, hypoxia and fish kills (Nixon et al. 1995; Cloern et al. 2001; Diaz and Rosenberg
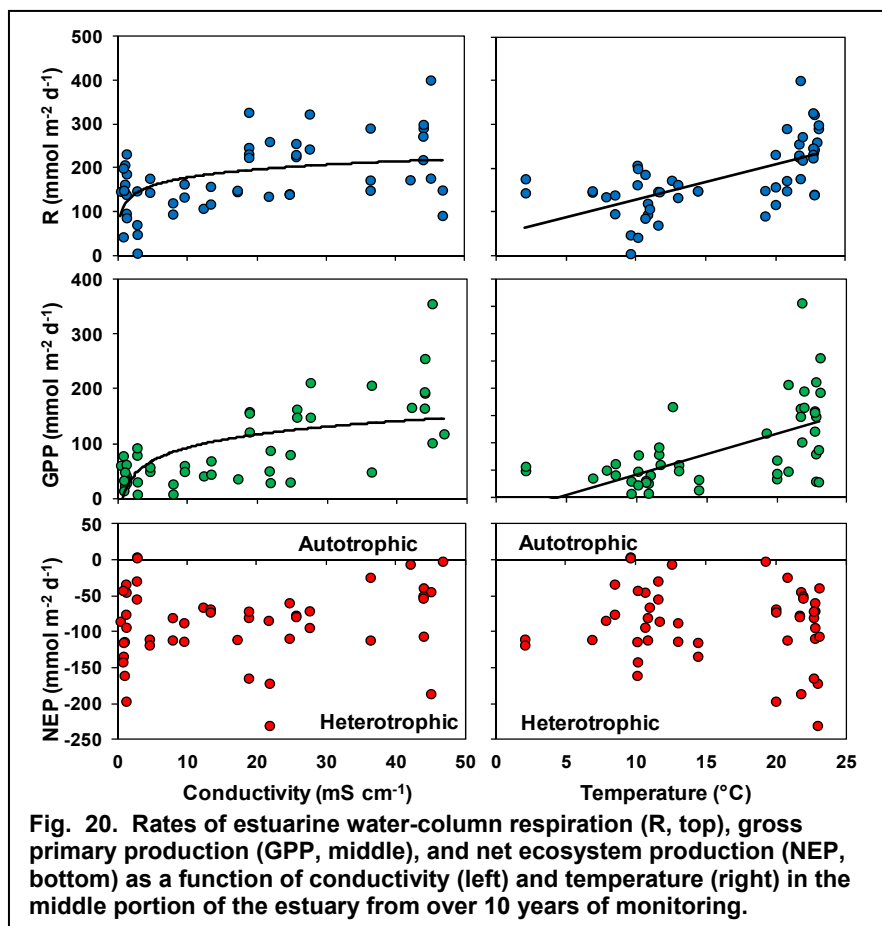
2008). In contrast, rates of production and respiration in the PIE estuary are typically highest in mid-summer, when discharge and inputs of nutrients and organic matter from the watershed are lowest. Low discharge leads to longer residence times and up-estuary movement of saline waters (Vallino and Hopkinson 1998). Our work to date has elucidated the role of the benthos in fueling production in the estuary when watershed inputs are low (Giblin et al. 2010; Weston et al. 2010), and the strength of the coupling between the watershed and the estuary, but the importance of marsh inputs of nutrients and organic matter fueling metabolism have not been quantified. Further, the degree to which estuarine metabolism will respond to changing marsh geomorphology and increased flooding and drainage of low elevation marsh areas is unknown. In addition to changing plant species composition and thus organic matter sources (H2.1), we expect a higher number of creeks and more frequent marsh flooding (H1.1) will result in greater flushing of creekbanks. Our process level measurements suggest that the creekbanks are hot spots for N cycling and that processes such as coupled nitrification/denitrification occur at much higher rates in creekbanks with effective drainage. Our proposed work will address how estuarine metabolism is coupled to watershed, benthic, and marsh sources of nutrients and organic matter that vary over space and time, and how changing marsh-estuarine geomorphology together with climate change and human activities in the watershed will influence estuarine C and N cycling.

Approach:
We will continue monitoring activities focused on estuarine metabolism that will provide information on the response of the estuary to long-term changes in land use, climate, and sea level. New efforts in PIE IV will use a space-for-time approach (H1.3) to assess the influence of marsh connectivity on estuarine metabolism and biogeochemistry. Monitoring activities will be expanded to six tidal creek systems described in H1.3 (Fig. 12). The space-for-time approach, combined with our long-term monitoring, will address the response of the estuary to the expected changes in geomorphology, providing a basis for understanding long-term trends in estuarine metabolism.

Long-term monitoring: We continuously monitor water column metabolism (GPP, R, NEP) at 3 stations along the length of the Parker estuary using *in situ* water quality instruments. This monitoring is supported by whole estuary transects run twice per year (during high flow in the spring and low flow in late summer) at dawn and dusk for consecutive days. Changes in dissolved oxygen, after correcting for air-sea gas exchange, are used to quantify estuarine metabolism. We measure nutrient chemistry, chlorophyll, and phyto- and zoo-planktonic community composition in the water column. In conjunction with these measurements we measure benthic metabolism, benthic nutrient exchange and sediment N dynamics (denitrification and DNRA) at several locations. We also measure benthic chlorophyll and sediment C and N content. The contribution of the marsh to nutrients, DOC and DIC in tidal waters is estimated using porewater measurements and creek bank drainage measurements.
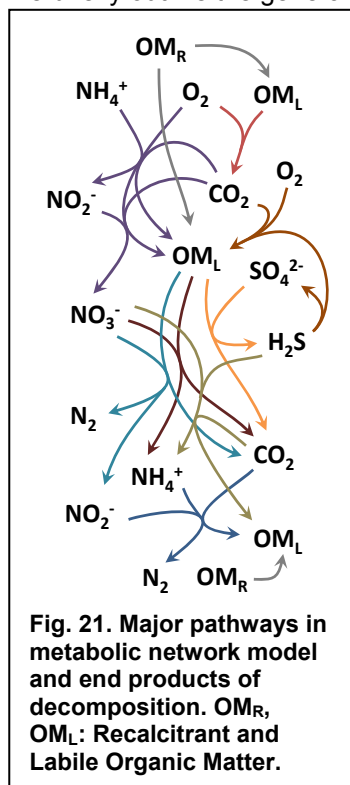
New Activities: During PIE IV, we will expand the monitoring program to focus on understanding how the various components of the watershed-marsh-estuary system interact to influence system metabolism. Aquatic metabolism transects will be expanded to include a mid-summer measurement on the Rowley and Parker River Estuary. The spring transect consistently captures the cold, high discharge condition in the estuary, but the late summer transect has been more variable and may include either high or low flow conditions. The inclusion of a mid-summer transect at near-maximum temperatures and near-minimum freshwater flows for the system will enhance our ability to model metabolism in the system as a function of key external drivers. Expanding transects to include the Rowley River will yield information on estuarine metabolism in a system with more direct connectivity to low elevation marshes which is a growing focus of our research efforts.

To understand how the transition from high to low marsh will influence estuarine water-column metabolism, we will couple our ongoing estuarine transects with metabolism and tidal exchange measurements made in a space-for-time approach in 6 smaller tidal creeks. In tandem with measurements of sediment (H1.3) and carbon exchange (H2.1), we will measure the exchange of carbon (DIC, DOC, POC) and nutrients (NH_4^+, NO_3^-, PO_4^{3-}, DON) 6 times per year between the marsh and the estuary as described in detail in H1.3. Creeks will be instrumented for continuous measurement of stage, conductivity, temperature, dissolved oxygen, CDOM, turbidity, and pH, and sampled periodically for C and nutrients by automated samplers (pairs of creeks will be instrumented for one week rotations). Discrete sampling will be used to calibrate the higher time-resolution probe measurements. These creek monitoring activities will yield estimates of C and nutrient exchange between the estuary and marshes of different elevation. To help partition marsh vs. open water sources of production and respiration, we will use bioassays. Water collected during flood and ebb tides during our tidal creek occupations will be

incubated at various light levels at *in situ* temperatures. Rates of aquatic R, GPP, and NEP will be measured (changes in O_2 and DIC) along with changes in nutrients and organic C to determine how aquatic primary producers respond to nutrients and how aquatic heterotrophs respond to the quality and quantity of organic matter draining high and low marshes. We will combine this information with measurements of marsh C and nutrient exchange with the open channel. This will allow us to partition metabolism within the open channel from respiration of marsh-derived organic matter and the export of metabolites (DIC and O_2) from the marsh. Taken together with measurements of marsh production and benthic metabolism, we can more fully partition metabolism and C cycling throughout the system and, through long-term monitoring, gauge how each component is responding to sea level rise, climate change and human activities.

   Increased connectivity between the marsh and estuarine waters may also increase rates of coupled nitrification-denitrification. We will evaluate the relative importance of denitrification and N cycling in the 6 creeksheds using two techniques. First, in conjunction with tidal flux measurements in the creeks, we will seasonally assess denitrification by sampling N_2/Ar concentrations in discrete water samples collected over several tidal cycles. We have begun these measurements using several noble gases to calculate the "excess air" draining from the porewater, a calculation that is needed in order to use the N_2/Ar technique in creeks. Second, we have been able to adapt the push pull method of Koop-Jakobsen and Giblin (2010) to areas nearer to creek banks where drainage is higher and this will allow us to also measure DNRA. These approaches will allow us to assess rates of N cycling throughout the marsh complex (creek edge to marsh interior) in both low and high marshes with a focus on creekbanks as hot-spots.

Biogeochemical Modeling (H2.1 and H2.3) - We have developed a theoretical framework for describing microbial biogeochemistry as a type of dissipative system governed by maximum entropy production that forms the basis of the modeling approach (Vallino 2010, Vallino 2011; Algar and Vallino 2014; Vallino et al. 2014). The MEP model is founded on the hypothesis that microbial communities evolve, adapt and organize to extract as much free energy from the environment as available resources (N, P, S, etc.) and information allow. Continuous turnover of the community by predator-prey dynamics prevents net biomass accumulation, so effectively the community simply converts chemical potential into heat (as proposed by Lotka 1922), which is the definition of thermodynamic entropy. Information stored in the metagenome determines the set of molecular machines (Falkowski et al. 2008)—catalysts in particular—and metabolic functions that can be constructed from the available environmental resources. We briefly outline the general MEP approach below, but see references above for details.

Fig. 21. Major pathways in metabolic network model and end products of decomposition. OM_R, OM_L: Recalcitrant and Labile Organic Matter.

Under the MEP paradigm, we view microbial systems simply as a collection of catalysts that increase and decrease in abundance so as to maximize the rate of energy dissipation subject to stoichiometric, kinetic and informational constraints. We represent these constraints with mathematical expressions that lend themselves to simulation modeling, but use parameters judiciously. For stoichiometric constraints, we use a distributed metabolic network (Vallino 2003) where each functional pathway consist of an energy liberating redox reaction (such as $CH_2O + O_2 \rightarrow CO_2 + H_2O$) that fuels a biosynthetic reaction that produces a "catalyst", $\mathbb{S}_i$ (such as $CH_2O + \gamma NH_3 + \delta H_2PO_4 + \cdots \rightarrow \mathbb{S}_i$) that is unique to each functional pathway. An optimal control variable determines how much catalyst is synthesized versus how much energy is dissipated for each functional reaction represented in the network (Fig. 21). For kinetic constraints, we have developed a modified Monod equation that is able to capture bacteria growing under oligotrophic conditions (i.e., doubling times >> 1 day) to those observed under ideal laboratory conditions (doubling times < 20 min) using the same control variable that regulates reaction stoichiometry (Vallino 2011). Informational constraints are imposed by the metabolic network used to represent the community. Most of the MEP model's degrees of freedom reside in the optimal control variables rather than a large set of parameters whose values are poorly known.

We plan to extend our maximum entropy production (MEP)-based modeling to better predict biogeochemical processing on the marsh platform and links between marsh and estuarine production. Two 1D MEP-based models will be developed using two different approaches for solving the MEP optimization problems (Fig. 22). Both models will use data from long term monitoring and new information collected in conjunction with the tidal creek monitoring and marsh porewater measurements. Additional information from nutrient enriched creeks (TIDE) will inform the models (e.g., Koop-Jakobsen and Giblin 2010).

For the marsh platform (H2.1) we will use MEP-OC, a 1D vertical (z) model where the MEP solution will be found using receding horizon optimal control as previously developed (Vallino et al. 2014), but extended to 1D. Changes in marsh productivity are caused by changes in the extent and duration of marsh flooding and associated C and N loading, so understanding the microbially dominated process of decomposition is paramount. To develop a model that can predict how changes in organic matter (OM) and dissolved inorganic N (DIN) loading affect sediment respiration and N and S cycling, we plan to extend our existing 0D MEP model on anaerobic nitrate reduction (Algar and Vallino 2014) by accounting for aerobic and sulfur biogeochemistry along a 1D depth profile. Specifically, we plan to extend the metabolic network to include aerobic heterotrophy, ammonium and nitrite oxidation, aerobic sulfide oxidation, sulfate reduction, and anaerobic sulfide oxidation by nitrate (Fig. 21). The model will be calibrated and tested with geochemical, porewater, and rate measurements in high versus low marshes using our space for time approach.

Fig. 22. Applications of the two 1D models: MEP-Darwin longitudinally in the water column and MEP-OC vertically in the sediments.

In the estuarine water column, a 1D longitudinal (x) model, MEP-Darwin, that runs from the southern mouth of PI Sound to the head of the Parker River will be based on a Darwinian solution to the MEP problem. Changes in OM and DIN loading to the estuary from the watershed and drainage from marshes alter estuarine biogeochemistry and metabolism (H2.3). Our approach will be to modify our existing 1D estuarine metabolism model (Hopkinson and Vallino 1995; Vallino et al. 2005) by replacing the conventional biogeochemistry model with one based on a metabolic network (similar to that in Fig. 21). The metabolic network will include aerobic heterotrophy, nitrification, sulfide oxidation and aerobic phototrophy. As described above, we can determine how partitioning of catalysts to reactions vary over time by solving an optimal control problem (Vallino 2010; Algar and Vallino 2014; Vallino et al. 2014). While this approach works well for zero-dimensional problems and has been extended to 1D problem with some success, the optimization procedure becomes computationally demanding for 2 or more dimensions. We believe a Darwinian approach developed for ocean biogeochemistry models (Follows and Dutkiewicz 2011) can be used to solve the MEP problem. The Darwin model uses a combination of Monte Carlo-like simulations coupled with Darwinian-like competition that allows the model to find the optimum solution for a given subset of traits or phenotypes (functional groups) from the set of all possible traits. This approach has been tested with our simple two-box MEP ocean model (Vallino 2011) and it has been able to locate MEP solutions. However, we have found that locating MEP solutions does depend on the nature of the food web connectivity as expected from consumer-resource (C-R) theory (McCann 2011). Interestingly, we have learned that unstable C-R configurations (see McCann 2011) can find MEP solutions, while stable configures do not. We plan to study this result further, but our current hypothesis is that microbial communities are indeed unstable, and there is some experimental evidence that supports this (Fernandez et al. 1999, Graham et al. 2007, Beninca et al. 2008). We plan to use the Darwin approach for solving the MEP problem in the estuarine water column along a 1D transect. We will populate the MEP-Darwin model with the functional groups described above and allow C-R competition to locate the MEP optimum. We have already implemented some test cases in 1D, which show promise for solving the MEP problem, but with much less computational overhead. Consequently, this approach should be extendable to higher dimensions, as afforded by our Delft3D and ADCIRC models.
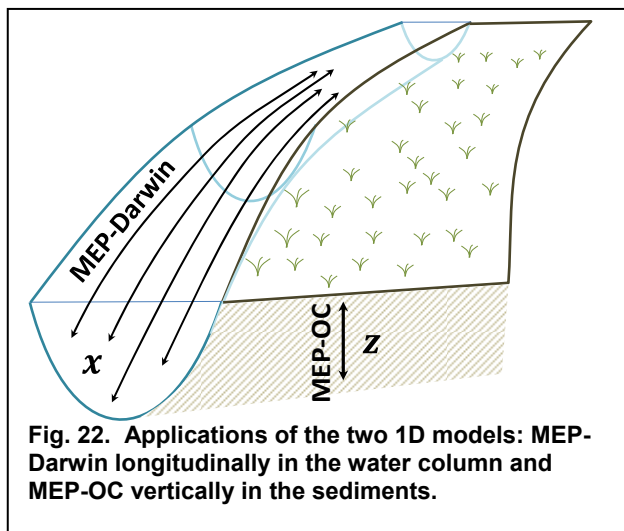
Q3) How will key consumer dynamics and estuarine food webs be reshaped by changing environmental drivers, marsh/estuarine geomorphology and biogeochemistry (Fig. 23)?

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.

Rationale: We are only beginning to understand how landscape-level variation in productivity, disturbance and habitat configuration control food webs (McCann and Rooney 2009; Wimp et al. 2011). Theory suggests two main effects. First, loss of habitat is likely to decrease species richness (Chase and Knight 2013; Keil et al. 2015) and food web complexity (Montoya and Solé 2003; Montoya et al. 2006). Second, habitat homogenization will decrease the variability and complexity of communities and food webs, leading to reductions in the rate of ecosystem processes at a landscape level (Byrnes et
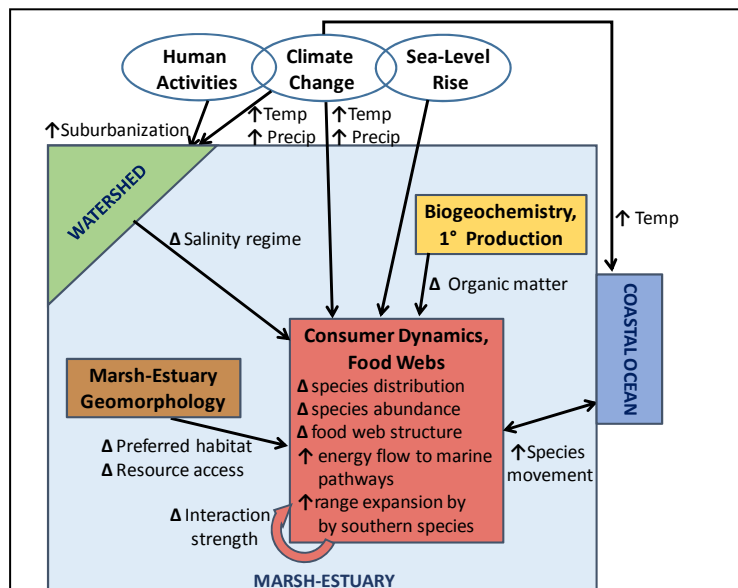

Fig.23. Conceptual diagram for Q3. Sea-level rise coupled with changes in habitat configuration and primary production will shift estuarine food webs to more marine pathways (H3.1), species movement with warming temperatures will alter food webs (H3.2), and environmental changes will favor omnivorous species that increase food web stability and mobile consumers that forage across habitat boundaries (H3.3).

al. 2006; Lefcheck and Duffy 2015). This is particularly salient in estuaries where habitat edges play key roles in ecosystem function (Wimp et al. 2011). In southern estuaries increased shrimp abundance (Haas et al. 2004) but lower growth of fish (Kneib 2009) is correlated with habitat complexity.

We found striped bass were consistently associated with salt marsh creek confluences with lots of edges that connect to open water (Kennedy et al. 2016). Our large-scale marsh nutrient enrichment experiment (TIDE) has shown declines in nekton production and the trophic subsidy to the open bay in the last 4 years as N enriched low marsh was lost (Deegan et al. 2012). We predict that the greater inundation associated with sea-level rise will allow mummichogs to feed on the marsh surface at higher trophic levels (Fig. 24), potentially inducing top-down control of marsh invertebrates (Fig. 25, Fig. 26) (Fleeger et al. 2008) and increasing trophic subsidies to the open bay (Baker et al. 2016). Hence, the future changes to marsh configuration and flooding may have cascading influences on functional roles and value of tidal marshes for organisms and estuarine food webs.

Approach:

Long term monitoring. We will continue and expand our long-term salt marsh creekshed monitoring along
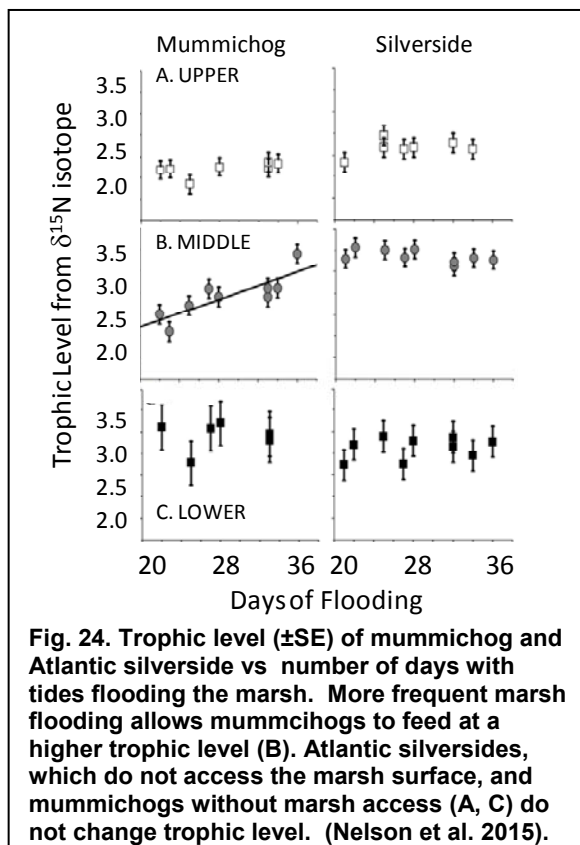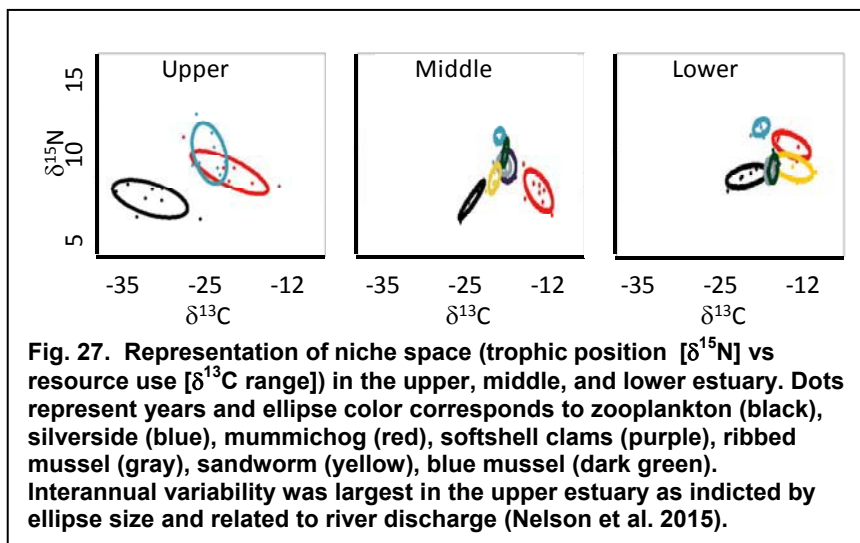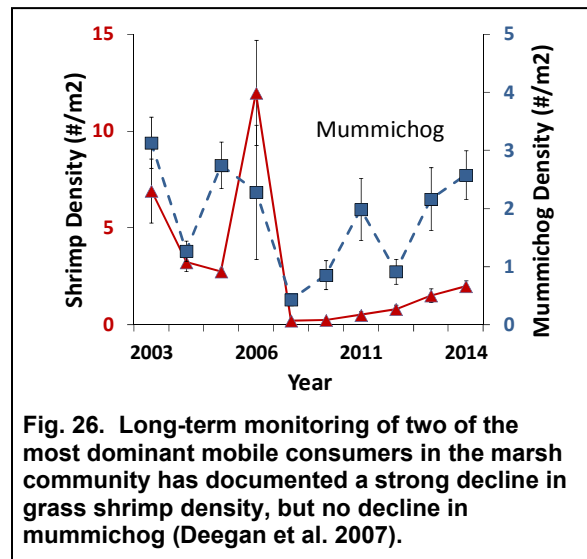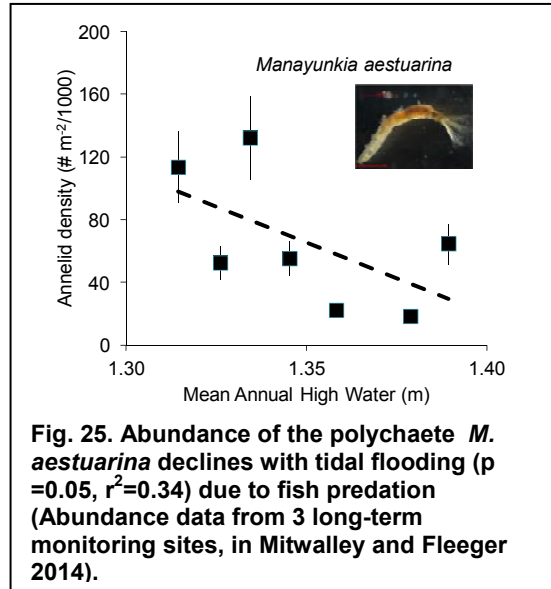

Fig. 24. Trophic level (±SE) of mummichog and Atlantic silverside vs number of days with tides flooding the marsh. More frequent marsh flooding allows mummcihogs to feed at a higher trophic level (B). Atlantic silversides, which do not access the marsh surface, and mummichogs without marsh access (A, C) do not change trophic level. (Nelson et al. 2015).

an inundation gradient from the creek channel to the low marsh to the high marsh platform. We measure the invertebrate community, small mobile consumer species, and vascular plant and algal characteristics. In our long-term sites, we will evaluate if marsh habitat and food web changes occur in line with our predictions over a decadal time scale. We will continue sampling in the open bay, and expand into the marsh, our core isotopic measurements of breadth of basal resources ($\delta^{13}C$, $\delta^{34}S$) and trophic position ($\delta^{15}N$) that will indicate shifts in species niche space (Fig. 27) with ecological conditions and pathways of energy flow (Fry et al. 2008; Nelson et al. 2015). Because complete isotopic sampling of individual species in an entire food web is impractical (e.g, in the marsh, we have 19 species of annelids and 38 species of copepods), we use a community module approach and have identified 10 key functional groups that span trophic levels and feeding modes (e.g, grazers, detritivores, filter feeders, intermediate consumers, top predators; Wilson 1999). We collect replicate composite samples (n>10 individuals per composite) of each species/functional group in the open bay, along the same transect from the upper freshwater to the lower marine estuary used for zooplankton and metabolism.

These measurements will allow us to relate basal resource use and trophic position in the middle estuary to decadal changes in marsh habitat and look for more dependence on marsh/open bay production (Fig. 28) We will also look for increased food web variability with the expected increase in variability of freshwater discharge (See Q2) in the upper estuary (Fig. 28B) Applying a Bayesian approach to stable isotope metrics allows for inclusion of uncertainty in comparisons of trophic structure across approaches and over time (Jackson et al. 2012; Abrantes et al. 2014). We will continue assessments of small mobile nekton in the open bay (started in 1994, 5 stations

Fig. 25. Abundance of the polychaete _M. aestuarina_ declines with tidal flooding (p =0.05, r²=0.34) due to fish predation (Abundance data from 3 long-term monitoring sites, in Mitwalley and Fleeger 2014).

Fig. 26. Long-term monitoring of two of the most dominant mobile consumers in the marsh community has documented a strong decline in grass shrimp density, but no decline in mummichog (Deegan et al. 2007).

Fig. 27. Representation of niche space (trophic position [$\delta^{15}N$] vs resource use [$\delta^{13}C$ range]) in the upper, middle, and lower estuary. Dots represent years and ellipse color corresponds to zooplankton (black), silverside (blue), mummichog (red), softshell clams (purple), ribbed mussel (gray), sandworm (yellow), blue mussel (dark green). Interannual variability was largest in the upper estuary as indicted by ellipse size and related to river discharge (Nelson et al. 2015).

along the main axis sampled every 3 years using 50m quarter circle set seines, 3 reps per station in June, July, August) and migratory birds and striped bass with our collaborators (USFWS, Parker River Wildlife Refuge, Mass Audubon Society, and MA Division of Marine Fisheries). New Work: To capture the full range of current and future salt marsh configurations for evaluation of the effects of total marsh area and the relative abundance of high to low marsh on food webs, we will conduct two sets of
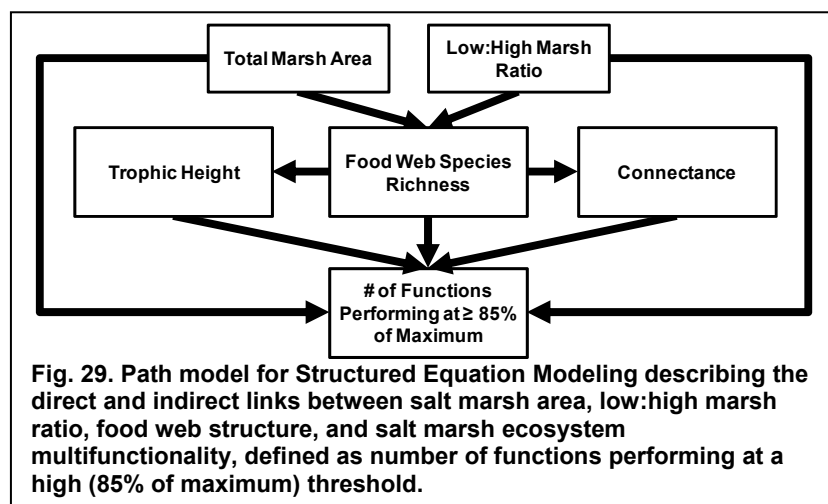
Fig. 28. Current (A) and predicted (B) isotopic distributions of basal resources (δ^{13}C range) and trophic position (δ^{15}N) as the estuary moves toward a system with more marsh and marine/open bay influences. In panel A, each point is an isotopic value for a year for 5 of the 10 community modules/functional groups in our long-term monitoring.
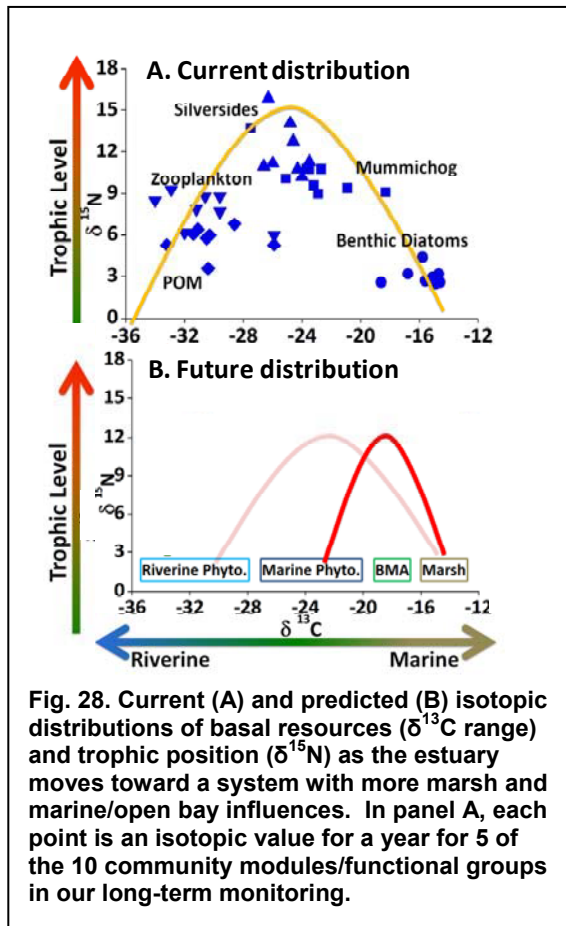
surveys. For the first two years, we will survey a large set of creeksheds (n=20) and then reduce our sampling to 10 creeksheds for the duration of the LTER. To tie the surveys into our existing long-term food web monitoring and new work on biogeochemical cycling, we will continue to sample our 3 long-term creeksheds in high marsh that overlap with the high elevation creeksheds and add the 3 new low marsh creeksheds (see Q2 and Fig. 12). This will allow comparison of food webs to other ecosystem functions. We will select 14 more creeksheds (n= 20 total) using a stratified, random sampling design by overlaying a 22x10 cell grid (0.4 x 0.4 km cells) over the PIE salt marsh domain (Wang et al. 2012). Sites will be selected to maximize orthogonality of total area and high-to-low marsh ratio. Ten sites, including the 3 long-term high and the 3 new low marsh creeksheds, will continue to be sampled annually. At each site, we will sample four transects for plant and animal abundance using standard LTER protocols (e.g., Deegan et al. 2007; Johnson et al. 2008; Morris et al. 2013; Johnson and Short 2013; Johnson et al. in press) and add some new measurements. Transect samples consist of quadrat sampling (n=5 per transect) for vegetation and macroinvertebrates spread evenly from creek to back marsh edge, pitfall traps to sample mobile invertebrates (e.g., small crabs and large amphipods), Breder traps along the creek edge (Warren et al. 2002) to capture data on highly mobile animals, infaunal and algal cores in the creek and on marsh, and vacuum and sticky trap sampling within quadrats to sample insect communities.

We will add new isotopic measurements (δ^{13}C, δ^{15}N, δ^{34}S) of functional groups on the marsh and standardized assays of potential herbivore (kelp substrate) and carnivore (squid substrate) consumption developed in a global marine biodiversity network (Duffy et al. 2015).

Modeling: We will use structural equation modeling (SEM) to determine the relationship between the landscape configuration and communities, food web structure and function (Bollen 1989; Grace et al. 2010; Lefcheck 2015) and to generate predictions about long-term changes. We will analyze the broad-scale survey data to evaluate how habitat change affects food web topology – species richness, food web connectance, trophic height, omnivory, trophic breadth, and average shortest distance to a basal resource (Fig. 29). This work will address whether reducing marsh area and high marsh conversion to low marsh reduces the diversity of species and food web complexity at the landscape level (Keil et al. 2015), how this translates to food web dynamics (McCann and Rooney 2009) via energy transfer, and whether these shifts alter ecosystem function (Byrnes et al. 2006; Poissot et al. 2013).
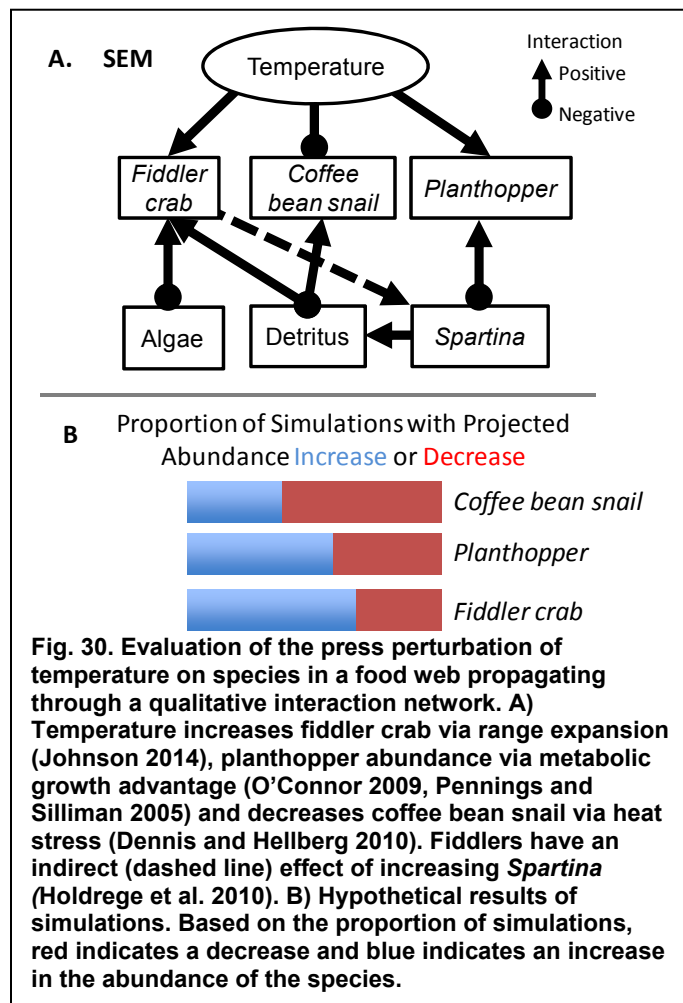

Fig. 29. Path model for Structured Equation Modeling describing the direct and indirect links between salt marsh area, low:high marsh ratio, food web structure, and salt marsh ecosystem multifunctionality, defined as number of functions performing at a high (85% of maximum) threshold.

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.*

Rationale: In 2014, we discovered the leading edge of a range expansion of the fiddler crab (*Uca pugnax*) at our long-term marsh sites (Johnson 2014). Our work and literature review confirms that PIE has no ecological history with any strong marsh creek edge burrowing species (Johnson et al. 2009, Johnson 2011). Vanguard populations may have stronger per-capita impact on ecosystem structure and function than their core populations. The lack of co-evolved competitors and predators in their new habitat allows niche expansion (Van Valen 1965; Bolnick et al. 2007) and more allocation to growth and reproduction instead of defense (enemy-release-hypothesis; Keene and Crawley 2002). Fiddler crab densities are low (<0.1 m^{-2}) relative to core populations such as those on Cape Cod, their historical northern limit (e.g., 120 burrows m^{-2}, Smith 2015). Fiddler crabs are ecosystem engineers that can modify the physical structure of marsh habitat (Jones et al. 1994), and influence primary production and nutrient cycling (Bertness 1985; Holdrege et al. 2010). PIE fiddler crabs may have stronger per-capita impacts and as densities increase over time, their impacts will increase. We anticipate that we can take advantage of the many LTER years of 'pre-fiddler' data and compare that to 'post-fiddler' data to understand the whole ecosystem implications of a new species on ecosystem function and structure.

New work: We will continue annual density measurements begun in 2014 in tidal creeks (n=8) where fiddler crabs are established and map their expansion with estuary-wide mapping every 2-3 years. Systematic annual surveys (n=20 quadrat counts over 200 m of creek; Johnson et al. 2014) allow us to follow colony density changes over time. New work to determine the spread of fiddler crabs will use the random sampling design developed in H3.1, with new creeksheds chosen according to a stratified random design. We propose that release from interspecific competition and predation will promote niche expansion expressed as increased between-individual variation in resource use (δ^{13}C) and that PIE fiddler crabs will have a larger body size and higher fecundity than core populations to the south (Little Sippewissett (MA), Nantucket (MA) and Narragansett Bay (RI)). We will also compare fiddler crab attributes in populations along the Atlantic Coast, including the Virginia, Georgia, and Florida LTERs to evaluate latitudinal variations in niche width. We will use a density experimentation relying on the natural aggregated burrow distribution of fiddler crabs (12 density-levels from 0-128 m^2; n=5 reps at each density) to measure impacts on creek-bank structure, primary production and food webs. Increased burrow density is expected to increase water flow through the creek bank (Q2.3), and alter bank characteristics (% water, organic matter, strength via penetrometer). Fiddler crabs are surface deposit feeders whose diet includes benthic microalgae (Grimes et al. 1989), thus we predict a strong effect on microalgae and a decrease in other infaunal abundances (Hoffman et al. 1984). We will also examine if indirect effects increase *Spartina* biomass (Holdrege et al. 2010; Johnson et al. in press). We will use the food web interaction strength modeling described below, but incorporate the indirect feedback of an ecosystem engineer (Fig. 30) to assess broader impacts.

Fig. 30. Evaluation of the press perturbation of temperature on species in a food web propagating through a qualitative interaction network. A) Temperature increases fiddler crab via range expansion (Johnson 2014), planthopper abundance via metabolic growth advantage (O'Connor 2009, Pennings and Silliman 2005) and decreases coffee bean snail via heat stress (Dennis and Hellberg 2010). Fiddlers have an indirect (dashed line) effect of increasing *Spartina* (Holdrege et al. 2010). B) Hypothetical results of simulations. Based on the proportion of simulations, red indicates a decrease and blue indicates an increase in the abundance of the species.

H3.3) Environmental changes will reshape community structure toward higher abundances of omnivorous species that increase food web stability and mobile consumers that forage across habitat boundaries.
Rationale: Ecologists have pursued two largely separate approaches to quantifying community structure, food webs and energy flow: 1) network topologies of feeding interactions (Polis et al. 1996; O'Gorman et al. 2010) and 2) the use of stable isotopes to understand trophic position and energy flow (Peterson and Fry 1987; Boecklen et al. 2011). Here we propose to use both approaches in modeling frameworks to evaluate how changing environmental conditions will alter relative species abundances and estuarine food webs. Three central problems arise in determining how perturbations affect food webs: 1) real-world complexity of topological networks and 2) the dearth of knowledge about trophic interaction strengths, and 3) how the feeding flexibility of some organisms reflects changing energy flow. We have a well-established food web topology network (over 56 papers in the LTER database), thus providing us with a complex network to analyze. We will approach the last two issues in two ways:

Modeling: We will apply new Bayesian *qualitative* modeling to *interaction strengths* that assesses press-driven abundance changes and quantify uncertainty in predictions. New Bayesian approaches using simulated strong and weak interaction strengths can be used to understand changes to community structure via changing relative abundance (Melbourne-Thomas et al. 2012, 2013). Bayesian approaches can also highlight areas of both certainty and uncertainty (Uusitalo 2007) and can be validated using long-term monitoring and the proposed 'space-for-time' experiment. Outputs of the Bayesian modeling will yield a probability of increases, decreases, or no change in abundance of species in response to shifts in high to low marsh (Fig. 30). We will start by modeling no more than five trophic links distant, as longer distances will lead to greater uncertainty in their outcome, but we will test this 5-link limit via a sensitivity analysis. As an example of how we will look at novel species, we will use the literature-based assessment of interactions of species south of Cape Cod that are beginning to arrive such as fiddler crabs. Prediction on the impacts of fiddler crabs on other infaunal abundances will be validated by measurements in Q3.2. We will compare site-level food web topology metrics to isotopic metrics (niche space, trophic breadth, and organic matter source) for communities in marsh and open bay sites where both are measured, including the ten long-term "space for time" sites. Differences between the two approaches will show to what extent species are flexible in their diets relative to what is available, which will indicate the potential for change in energy flow with structure changes (Kondoh 2003). This combination offers a new approach to understanding changes to food web topologies and energy flow patterns in response to diverse and interacting environmental drivers.

Cross-Site and Collaborations: Several collaborations are an integral part of the work proposed here. The first is a coastal SEES collaboration with the Virginia Coastal Reserve and the Georgia Coastal Ecosystems LTERs (McGlathery-VCR is lead; PIE PIs Morris and Giblin co-PIs). As part of this project we are carrying out *S. patens* organ studies, expanding our measurements of TSS across tidal creeks of various sizes in addition to the work proposed here, dating additional sediment cores, and carrying out a retrospective analysis in a small subsection of the marsh. Matt Kirwan (VCR) will use 1D point models to determine the threshold of sea-level rise for marsh stability at all sites and develop scenarios of marsh persistence. The socio-economic component, led by Robert Johnston (Clark U.) and former PIE PI Colin Polsky (FAU) will then use these scenarios to determine which wetland protection actions are favored by local stake holders. They will also examine the broader sustainability and economic value implications of adaptation options chosen. A second is a study lead by PIE PI Nat Weston (Weston, Morris, Craft & Neubauer; NSF DEB-1457442). This project is carrying out the controlled sediment additions described in H1.3 with assistance from PIE personnel. This experimental data will add to the field data being collected by PIE to help extend parameterization of the MEM model into *S. patens* and lead to a better understanding of the role of the vegetation in sediment trapping on the marsh. Morris and Hagen have been funding by USFWS to couple MEM with ADCIRC. PIE LTER and the NSF funded TIDE project (Deegan lead PI) have worked closely together. The TIDE project has contributed greatly to our understanding of the controls on consumers. Furthermore, information from the TIDE project on N cycling is used to inform our biogeochemical modeling. An additional cross-site project is just beginning. David Johnson will examine fiddler crabs from VCR and GCE to compare to the vanguard population at PIE to determine latitudinal variations in niche width.

We mention two other projects which are not essential to the research we have proposed here but which might otherwise appear to be important gaps. We have not included any work on the Plum Island barrier beach. The evolution of the beach was the subject of Chris Hein's Ph.D. Dissertation. Dr.

Hein is now at VIMS and continues to work on erosion and sediment redistribution on Plum Island and has other funding to examine beach erosion. We also have not proposed detailed process studies on ponds. Amanda Spivak (WHOI) and Rachael Stanley (Wellesley) and their student (Evan Howard) are examining pond metabolism and C losses. Giblin is on Howard's PhD. committee.

Modeling Uncertainty – Our models are designed to guide our research and to test our hypotheses, thus it is imperative to know their strengths and limitations. Uncertainty is usually assessed by comparing model output to data from either the field or highly constrained laboratory studies. However, there are many possible methods to perform this fundamental comparison (Brown et al. 2013, Duveiller et al. 2016, Pontius et al. 2011, Pontius and Si 2014). For example, conventional methods for assessing a continuous variable are based on squared differences, but those methods produce results that are difficult to interpret because larger differences receive disproportionately more weight than smaller differences in summary metrics. As a more interpretable alternative, we have been developing a method based on absolute differences, which builds on the innovative concepts we have published for a categorical variable (Pontius et al. 2008). We will use our new methods for categorical and continuous variables to measure the predictive ability of simulation models. Moreover, we will use examples from the LTER network to develop methods of spatially-explicit validation that are generally applicable.

In our model of responses propagating through interactions in marsh food webs (Q3), we are using a Bayesian framework in order to explicitly state our uncertainty in modeled prediction. These models are not expected to predict the true 'future', but instead provide a range of possible futures that have heuristic value for interpreting our 'space for time' experiment and for guiding future research. For other models we will determine parameter uncertainty and variability using a Monte Carlo analysis, defining parameter range based on field and laboratory measurements, thus obtaining an estimate of the confidence limits for each model result.

Synthesis – We will synthesize our work in three ways: 1) Modeling; 2) Project synthesis in a PIE LTER book; and 3) Leading broad ecological synthesis initiatives. _Modeling:_ Building, using, and refining conceptual and mathematical models tests our understanding of fundamental processes that govern coastal ecosystems. Models are used to guide our research, test hypotheses, make predictions, and to assess uncertainty. Our suite of mathematical models covers all aspects of our conceptual framework (Fig. 31). Because of the inherent complexity of one all-encompassing dynamic model with components that operate on different time and space scales (Murray 2003; Fulton 2010), we use the outputs of model simulations as initial conditions or inputs for other models (e.g. Alizad et al. 2016; Leonardi and Fagherazzi 2015). Cross-site collaborations in modeling, such as the use of Delft3D-SWAN by co-PI Fagherazzi at the VCR LTER, extend our work to systems with different climates, rates of sea-level rise, watershed development and a more diverse pool of species. These comparisons will deepen our understanding of how coastal systems may change in the coming decades. _PIE LTER Book:_ Led by Charles Hopkinson, lead PI prior to Giblin, we will complete a draft of a book for the LTER Science and Synthesis Series by the next 3-year review that synthesizes the long-term dynamics of Plum Island Ecosystems in the context of global
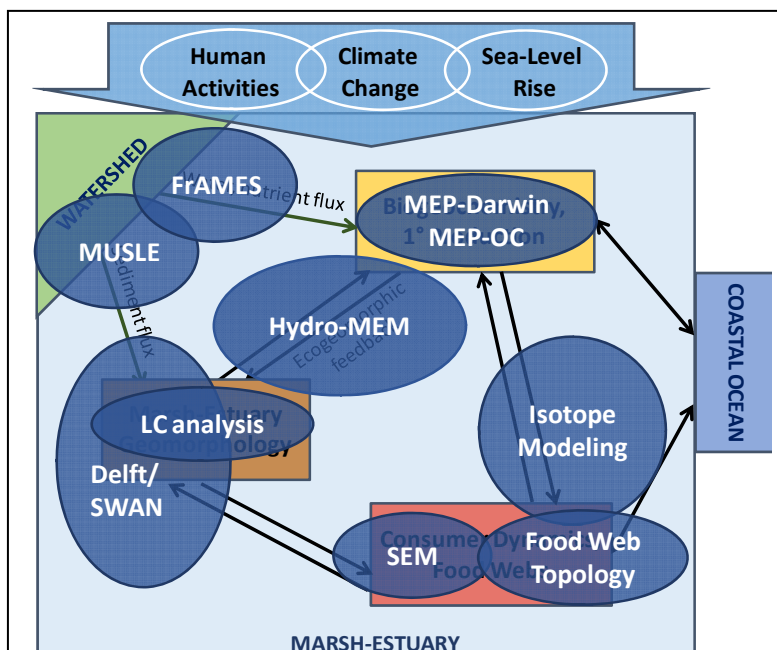

Fig. 31. Overview of models being used in PIE IV and how they cover all aspects of our conceptual framework (Fig. 4).

coastal environmental change. The synthesis will draw on research supported by the LTER, other NSF programs (e.g., Hopkinson, CNH - water use; Deegan, DEB-TIDE - nutrients impacts on salt marshes; Hein, Coastal SEES - barrier beaches and storms; McGlathery, Coastal SEES- Atlantic coast marsh sustainability), other government agencies (e.g., Morris, EPA; Giblin, CZM; Deegan, NOAA), and conservation organizations (e.g., Buchsbaum, Mass Audubon). The book will convey how this system has evolved since the last glaciation and the role human activities in the watershed and estuary have played and will continue to play in shaping this dynamic landscape. We will integrate across physical, biogeochemical, ecological and social disciplines using PIE as a model system for understanding the dynamic tension between climate change, human decisions and the persistence and function of marsh dominated coastal ecosystems. _Ecological Synthesis:_ We will continue as leaders in broad synthesis activities including: 1) writing papers to generalize our findings, such as the suite of synthesis papers in the September 2013 issue of Oceanography; 2) leading synthesis on broad ecological topics through scientific society symposia and the LTER network, such as the workshop on *"Spatial and temporal dynamics of key populations chosen to represent trophic levels"* being co-led by Deegan; 3) advancing new approaches in modeling and methods, such as Vallino has done with the MEP network and Forbrich's contribution to using flux towers in tidal systems; 4) working with management agencies, such as the work Giblin and Morris have done assisting CZM to parameterize and run the EPA SLAMM model on the impact of sea-level rise.

BROADER IMPACTS: This work will contribute to a better understanding of the process leading to coastal geomorphic changes and allow for better predictions of how these changes will alter coastal carbon and nitrogen dynamics. It will also help us understand how environmentally induced changes to species in a complex interaction network result in subsequent shifts in the abundance of key species, food web structure, and energy flow which is a fundamental challenge in ecology. The goals of the education and outreach programs at PIE continue to be to excite students and teachers about coastal science through hands on activities, to train the next generation of coastal scientists, to promote environmental stewardship, and to serve as a resource for addressing local, regional, and national environmental issues. Our work is valued and used by management agencies and these interactions continue to increase. The PIE LTER Education and Outreach program will continue to build on our accomplishments and the connections we have developed since the LTER was initiated.

Educational Activities - Our K-12 Schoolyard program will continue to engage area schools in the Salt Marsh Science Project under the direction of Education Coordinator Elizabeth Duff (Mass Audubon). A strength of this initiative is that it provides experiential learning opportunities for students and teachers in their own backyard, mostly at PIE. The program serves approximately 1000 students and 50 teachers per year in grades 5-12 in 10 schools. Initially focused on examining the changes in salt marsh vegetation due to tidal restrictions and hydrologic restoration, Duff will provide a new climate change focus that will make use of the vegetation transects she has been observing with teachers and students for the past 25 years. These permanently marked transects will be used as references for any changes in salt marsh vegetation due to sea level rise. Duff has brought in outside funding to engage the students in determining the most vulnerable areas in their communities and an assessment of how the salt marsh is fairing in their towns will be a great addition to their learning experience. Duff will also continue her partnership with the United States Fish and Wildlife Service and the Mass Bay Project in engaging students and other adult volunteers in controlling a new invasive plant, perennial pepperweed (*Lepidium latifolium*). In addition, Ms Duff has written or facilitated contributions to the LTER Education Network. In 2013 lessons from our striped bass curriculum (http://pie-lter.ecosystems.mbl.edu/content/striped-bass-curriculum), based on PIE research were updated to the LTER Digital Library. PIE researchers and teachers have been major contributors to the LTER wide "Data Nuggets" effort (http://datanuggets.org/) with 5 lessons on line and 2 in review.

PIE-LTER will continue to offer opportunities for high school, undergraduate, graduate, and post graduate students. The goal of all of our educational activities is to provide a high quality learning opportunity in ecological research under the direction of PIE scientists. As in the past, we expect that a number of these projects will be presented at regional and national scientific meetings and written up for publications. Typically 1-4 students a year in the MBL's Semester in Environmental Science Program conduct projects at PIE and many develop into independent senior theses at their home institution.

New Initiatives: The LTER will continue to collaborate with the Gulf of Maine Institute (GOMI-http://www.gulfofmaineinstitute.org/) to provide opportunities for high school students to learn scientific

and leadership skills through environmental stewardship projects throughout the Gulf of Maine. As a member of its Board of Directors, Giblin has been working with GOMI to expand this program to local community colleges. GOMI is currently working with Middlesex Community College to raise funds for students to do paid internships with PIE LTER scientists as well as local agencies. Scientists and faculty will lead students in hands-on field science with local agencies and scientists. Their work will focus on solutions to regional issues and thus include a civic engagement component. In New England, as elsewhere, the community college population is far more diverse than that of 4 year colleges and many students come from economically disadvantaged backgrounds. They receive little hands on training in STEM fields as part of their community college experience and hence are less likely to choose STEM careers. We believe providing flexible paid internships, is an effective way to reach this audience.

Outreach - Our outreach activities will continue to actively engage the public and connect with the management and NGO communities. The goal of these activities is to increase the knowledge of the general public and managers about environmental issues, particularly those addressing watershed, marsh and estuarine communities. This will be accomplished through lectures, writing articles in local newsletters and the media, and serving on advisory committees. Providing scientific input on the potential impacts of climate change and the consequences of land use changes will continue to be strong foci of our outreach. As an example of our impact, PIE scientists participated in regional and national level advisory panels to EPA, NOAA, USFWS, Mass CZM and several national panels examining restoration in the Gulf of Mexico and the aftermath of Hurricane Sandy.

PIE currently has two popular books in production. PIE scientist Colin Polsky has written a book for the LTER Schoolyard Series about the ecosystem impacts of lawn care practices. Under the working title *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. David Johnson has a popular-science book under contract based on his thirteen years, beginning as a graduate student, working in the marshes of Plum Island. It is tentatively titled *Marsh view: Revealing the Mysteries of the Great Marsh* and includes first-person accounts about the natural history of the marsh and the life of a young scientist. The book stems from a series of essays he published in the *Daily News* newspaper of Newburyport, Massachusetts.

Eight journalists participated in the 12-day hands-on Logan Science Journalism program at the PIE LTER in 2011 and 2015 and will do so again this summer. This program offers fellowships to mid-career science journalists and immerses them in ecosystem and global change science at LTER sites.

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Boxed Bold Citations are PIE Top 10 publications
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FACILITIES, EQUIPMENT AND OTHER RESOURCES

MARINE BIOLOGICAL LABORATORY

The Marine Biological Laboratory and The Ecosystems Center have well-equipped research laboratories. In the spring of 2001, The Ecosystems Center moved into a new 32,000-sq. ft. building designed specifically for the Center. This building includes a new analytical lab, which houses a new lab-wide nanopure water system, Lachet autoanalyzers, centrifuges, digital pH meters, two UV-Visible Shimadzu spectrophotometers, two Turner fluorometers, infra-red gas analyzers, Dionex ion chromatographs, gas chromatographs with TCD, FID, and ECD detectors, epifluorescence microscopes as well as digitizing equipment for bacterial size determination, and autoclaves. Our lab is well equipped for metabolism measurements including an Apollo analyzer for high precision DIC analysis, an optical oxygen system, and a high precision winkler titrator. The Ecosystem Center has incubators, constant temperature rooms and also owns and maintains four environmental chambers that can control set points for temperature, and light intensity and duration. We also have several vans and cars that are available at reasonable cost. The Ecosystems maintains a stable isotope facility that runs samples for a reasonable cost. The lab utilizes both Dual- Inlet and Continuous-Flow Isotope Ratio Mass Spectrometer systems for the measurement of $\delta^{15}N$, $\delta^{13}C$, $\delta^{18}O$ and δ^2H on various types of samples. Both natural abundance and isotopically enriched samples can be accommodated. Giblin's lab operates a membrane inlet mass spectrometer system (MIMS), which is used for the denitrification and DNRA measurements. This system includes a specially designed gas inlet system attached to a Balzers quadrapole MS designed by Todd Kana, Bay Instruments (www.hpl.umces.edu/dga/DGAhome.htm). We have retrofitted a furnace onto this machine to allow for the measurement of the isotopes (30, 29 and 28) of N_2.

Ecosystems Center computer facilities include 6 SGI workstations for general use, as well as an eight CPU SGI Origin and approximately 100 PC computers and workstations. All computers are interfaced through a local Ethernet link that is connected directly to the Internet. Numerous color and black and white printers are available, including a large format printer for poster preparation.

The Marine Biological Lab has several liquid scintillation counters, a Perkin-Elmer 2400 CHN analyzer, a Perkin-Elmer atomic absorption spectrometers, refrigerated centrifuges, scanning electron microscopes, video-linked microscopes, digital microscopic analysis, and various balances, freezers, a -80^oC freezer to preserve DNA samples, and dissecting scopes available for our use.

The MBL purchased the "Marshview Farmhouse" in Newbury for PIE field use. The facility had a very small basic field lab for processing samples but was greatly improved in 2014 with NSF funds from Field Stations and Marine Lab grant which allowed us to put a 1,300 sq ft addition on to the barn and create high quality laboratory space (described in more detail under site management, Section 3). The PIE LTER program maintains a number of field installations for monitoring on site. These include a weather station at Marshview, two eddy flux towers for measuring the exchanges of CO_2 and water between the marsh and the atmosphere, a network of water quality monitoring sondes in the estuary, pressure sensors for recording water levels in wells in the marsh and in the estuary, and a NOAA quality tide gauge near the southern entrance to Plum Island Sound. Last year we field tested a SeapHOx for the continuous measurement of pH, oxygen, temperature and conductivity and it will be deployed near the tide gauge next summer. Our server is located in a nearby rental property (also described in section 3) and communicates with the sondes and the eddy flux towers via radio.

The LTER has a variety of field equipment on site including three boats for inshore coastal use, several current meters, field instruments for monitoring water quality, a canopy analyzer, a Unispec for reflectance measurements, and the normal array of needed field gear such as plankton and zooplankton nets and tools.

FACILITIES, EQUIPMENT AND OTHER RESOURCES

Other Resources – The Parker River National Wildlife refuge allows the LTER educational and science programs to use their auditorium for larger meetings and their classroom space for smaller meetings.

BOSTON UNIVERSITY

The Coastal Geomorphology Lab is equipped with:
- Zodiac Inflatable Boat RIB Pro7 with 40hp Yamaha motor
- tripod frame
- one Sontek ADV for waves and currents measurements
- five OBS D&A Instrument Company for measurement of sediment concentrations
- four Nortek ADCP velocity profilers
- two TWR2050 Tide and Wave Recorders
- two steel tripods for tidal flats deployments
- one Partrac Cohesive Strength Meter for sediment critical shear stress measurements
- one Topcon Total Station
- Two Nortek Vector ADV
- one NexSens submersible datalogger with salinity and chlorophyll a probes
- one HOBO weather station
- one PA 500-6 Tritech altimeter for erosion
- one MiniWater6 velocity probe for velocity measurements
- one Hiperlite Topcon GPS rover and station
- one Waltz Diving PAM

CLARK UNIVERSITY

Clark University has resources required for the subcontracted components of the proposed project. These resources are housed in the following parts of Clark University.

The **George Perkins Marsh Institute** (GPMI; www.clarku.edu/departments/marsh) conducts research funded by agencies such as the EPA, NIH/NIEHS, NSF, NASA, DOE, National Park Service, as well as state and local governmental agencies and private foundations. GPMI provides office space, support services, and up-to-date computing resources that include high-speed network capability and internet access, maintained by the Clark Information Technology Service department, as well as computer workstations and software required for various types of statistical, geographic and other quantitative analysis, e.g., SAS, Stata, LIMDEP/NLOGIT, TerrSet, ARC/INFO, MatLab. The Marsh Institute is staffed by a full-time Program Manager, who is responsible for daily operation and budget management, as well as communications, graphic and web-design professionals. The Marsh Institute has provided the facilities, resources and expertise to implement numerous prior projects.

The **CoFERT Lab** is maintained by both GPMI and the **Clark University School of Geography** (www.clarku.edu/departments/geography). The CoFERT Lab has 10 Windows NT Workstations connected to a Digital Priorix server with 14Gb of disk space. All workstations are PI1350 or higher with 128Mb RAM and 10Gb to 37Gb hard drives. The machines are connected to the domain with 100Mb switches and to the University hub with a 10Mb switch. The University is connected to the Internet with T1 cable. The lab has licenses for IDRISI, ARC GIS, eCognition/Definiens, ATLAS.ti, and ERDAS Imagine, in addition to the standard suite of statistical and spreadsheet/word processing/presentation softwares, such as GRASS 4.0, Image Processing Workbench, GEO/SQL, SPANS, Splus, Spacestat and FRAGSTATS, MS Office, SPSS, and C++ and Visual basic programming compilers. Other input and output devices include one Calcomp digitizing tablet, one large format color plotter, a thermal color

FACILITIES, EQUIPMENT AND OTHER RESOURCES

printer, a film writer, color scanner, CD-ROM/DVD writers, and a VCR and frame grabber. Field equipment consists of 20 Geo-positioning Systems (GPS) units, measurement tapes, compasses, weights, spherical crown densitometers and surveying equipment.

MASSACHUSETTS AUDUBON SOCIETY

Mass Audubon has standard equipment for field sampling of plants, fish, birds, and other biota, such as binoculars, spotting scopes, rangefinders, tapes, quadrats, beach seines, nets, hand held GPS units, etc. Sieves and microscopes and are available for sorting and analyzing benthic samples. Massachusetts Audubon owns 240 acres of salt marsh and surrounding upland in the Plum Island Sound estuary that is the locus of some of our field studies. The organization also has two facilities in the region that could be used by the PIE LTER for meeting space. These are the Joppa Flats Nature Center in Newburyport and the Endicott Regional Center in Wenham. The latter houses computer facilities for Mass Audubon's participation in the LTER.

UNIVERSITY OF MASSACHUSETTS, BOSTON

Laboratory: On the UMB campus, students will be housed in the PI's fully equipped research laboratory in the new UMB Integrated Sciences Complex. The lab is fully supplied with multiple Apple computers, a fume hood for sample processing, sample freezer, a full range of shop tools, dissecting scopes, and other equipment for lab work.

Computer: UMass Boston has extensive computer resources for this project. Each research lab has an array of internet- connected Macs and PCs. UMB has 10 computer labs with over 250 PCs and printers available for student use, as well as specialty computer facilities and computer teaching laboratories. The University has licenses for all necessary software beyond use of open source tools (i.e., MATLAB, ArcGIS) although open source tools (R, Python) are prefered. The PI will provide computer facilities in his lab for student work. We also have access to a Ravana, a 128 core server for High Performance Computing where necessary.

Major Equipment: Our lab at UMB has a Ford F-150 for use by lab members in transport to, from, and around field sites.

UNIVERSITY OF NEW HAMPSHIRE

Field and Lab Equipment Available to Wollheim (Earth Systems Research Center and Department of Natural Resources and Environment)
Wollheim maintains a set of four in situ nitrate sensors (Satlantic SUNA), at least one of which will be devoted to this project. Other sensors currently owned and that will be committed to this this project include six Onset Hobo LDO Dissolved Oxygen Loggers, three Onset HOBO pressure, temperature, PAR, and conductivity loggers, a GPS logger, and a Campbell Scientific Cr1000 datalogger. Wollheim lab also has two handheld conductivity meters, a dissolved oxygen meter, and both Marsh McBirney and FlowTracker current meters for water velocity and discharge measurements. Wollheim has several Sigma autosamplers that can be used for automated water (grab) sampling during slug additions (e.g. night time sampling).

Necessary desktop computing resources are available at UNH for all faculty, staff, and students, including four desktops and two laptops with MATLAB installed, and two desktops with ArcGIS 10.2.1 licenses. The newly renovated Earth Sciences building at UNH (James Hall) provides sufficient office space and a productive working environment. UNH maintains a current library with a full range of hydrologic and biogeochemical journals.

FACILITIES, EQUIPMENT AND OTHER RESOURCES

Reach and network scale samples will be run at cost per sample at the UNH Water Quality Analysis Laboratory, which has extensive analytical capabilities. They include a Smart Chem robotic automated colorimetric analyzer for analysis of nitrate, Dionex ion chromatographs for simultaneous determination of cations and anions, a Shimadzu TOCV TOC/TON analyzer for measurement of dissolved organic matter, and a Horiba JY fluorometer that analyzes the spectral signature of dissolved organic matter. General equipment available in support of this project includes muffle furnaces, drying ovens, 2 large incubators, autoclave, freeze dryer, hoods, sinks, walk-in freezer, walk-in refrigerator, acid-washing dishwasher, and ultrapure water (RO followed by Millipore Milli-Q with UV polishing) for reagent and standard preparation.

ESRC Computing Facilities (Wollheim)
The *Earth Systems Research Center's (ESRC) Science Computing Facility (SCF)* has a wide range of computer servers, printers, plotters, archiving systems, software, data archives, and web based data distribution systems that are integrated using several internal networks and connected to the outside world through a high speed pipe. The overall *SCF* administration is provided by the *Research Computing Center* (*RCC*) located in the *Institute for the Study of Earth, Oceans and Space (EOS)*. Scientific data processing and analysis support is distributed throughout workgroups within the center with additional centralized expertise provided by *CSRC*'s *Laboratory for Remote Sensing and Spatial Analysis.* Within this proposal, we take advantage of this existing computer infrastructure, to meet our anticipated computational needs.

The main *ESRC* servers consist of high-end, multi-processor computing systems manufactured by Dell and SUN Microsystems. The Dell systems run Linux and are used for CPU intensive jobs, parallel modeling, and storage. They include several multi-node Beowulf clusters with over 25 Terabytes (TB) of RAID5 disk space, over twenty dual-CPU servers with a combined capacity in excess of 70 TB of RAID5 storage, and several other application and web servers. The Sun system is a Sunfire 280R that operates as both an application server and as the backup/archive server. Backups and archives are done using the Networker product from EMC. Most of the main servers share a gigabit (Gb) switch with the archive/backup system for high-speed communications. Nearline storage is done on a tape library unit. The tape library is a 120 slot Qualstar 46120 unit with 4 AIT-3 drives capable of 12.0 TB of native storage. All of this equipment is kept within a physically secured, humidity and temperature controlled machine room with UPS power. Final data and image products are produced from several ink-jet plotters and laser printers within the department. Additionally, several CD/DVD writers are used for data distribution.

ESRC also leverages the center's *Laboratory for Remote Sensing and Spatial Analysis*, a spatial information processing, analysis and distribution research laboratory. This laboratory provides geographic information system (GIS), Web Mapping, spatial data archiving, data distribution, remote sensing, image processing, cartography, large format printing and scanning support to several *ESRC* and *EOS* research projects. Staffed by professional geo-spatial information technicians, computer programmers, and graduate and undergraduate university students, the laboratory houses a multiple seat dual and quad core Linux, PC, and Mac OS computer cluster supplied with a variety of open source Remote Sensing, GIS, web mapping, image processing and cartography software and ESRI ArcGIS, Leica ERDAS Imagine, and IDL/ENVI, commercial site, block, and individually licensed GIS and Image processing software.

UNIVERSITY OF SOUTH CAROLINA
FACILITIES: Morris manages a 1031 ft^2 laboratory at the University of South Carolina, Columbia campus that is set up for analyzing samples typical for a field biology program. The lab has equipment for wet chemical analyses of water and soil (Lachat FIA autoanalyzer, Shimadzu spectrophotometer), plant ecophysiology (LiCOR 6200, Walz PAM fluorometer, GER 1500 Spectroradiometer, Turner Fluorometer),

as well as drying cabinets, balances, muffle furnace, etc.   The students have desk top computers in their offices equipped with Matlab, SAS, and ESRI ArcInfo.

OTHER RESOURCES: The Baruch Institute manages a flowing sea water facility on the Columbia campus that is available to faculty and students. The facility also houses walk-in climate controlled growth chambers.   We use the sea water and growth chambers for cultivating marsh vegetation.

The Baruch Institute's field laboratory in Georgetown, SC, consists of a 24,000 ft^2 research lab, with a seawater pier/ met station, 1600 ft^2 boathouse (16 boats) -900 ft^2 maintenance shop complex (11 vehicles), and a 3000 ft^2 running sea water laboratory. The main research building contains 22 labs and 13 offices, library, computer laboratory, wet teaching laboratory, conference and teleconferencing facilities, photographic darkroom, and a state-of-the-art analytical chemistry lab. Computer facilities at the lab are also excellent. Three modern dormitory buildings that accommodate 52 persons, and three cabins (7 persons each), all equipped with kitchens, provide living space for visiting students and researchers. A 2950 ft^2 conference lodge is also available. The Baruch Marine Field Lab (BMFL) has a resident staff of 28.

The BMFL has a data archive with a 40 year history of biological, oceanographic, geological and meteorological data. Germaine to this project are the Spartina primary production data (monthly biomass, stem density, and growth) that started in 1984 and the marsh elevation data set (Sediment Elevation Table data) that was started in 1996. Both data sets are ongoing. The BMFL is host to the North Inlet-Winyah Bay NERR, and hosts NOAA's Centralized Data Management Office for the NERR (National Estuarine Research Reserve network.

VILLANOVA UNIVERSITY

LABORATORY: Weston occupies a research laboratory within the Department of Geography and the Environment at Villanova University. Laboratory space totals 1400 square feet and includes analytical instrumentation to complete the proposed work. These facilities are well supplied with chemicals, reagents, standard and specialty glassware, pipettes, pH meters, balances, hotplates, ovens, centrifuges, and a deionized water system. In addition, the PI has access to an environmental chamber, a greenhouse, and a shared equipment room at Villanova University.

OFFICE: Weston occupies a private office within the Department of Geography and the Environment at Villanova University with access to support services. Dell Latitude E6420 laptop for office and travel use, a Dell Dimension laptop for field use, and a Dell Optiplex 755 desktop for dedicated laboratory use.

RESEARCH VESSEL: A boat (2007 G3 17' aluminum boat) with outboard motor (20 hp Yamaha) are dedicated to field work associated with this proposal and other current support.

EQUIPMENT: The following equipment is housed within my laboratory, the shared equipment room at Villanova University, or within other faculty laboratories which I have access to:
- Canberra Low Energy Germanium Detector for gamma spectroscopy (^{7}Be, ^{137}Cs and ^{210}Pb)
- Trimble 5800 Kinematic GPS System for high-accuracy mapping
- Agilent 6890N Gas Chromatograph with flame ionization and thermal conductivity detectors for CH_4 and CO_2 quantification in gas samples
- Leco TruSpec CN Analyzer for soil carbon and nitrogen analyses
- Raytest Raga Star beta emission detector for $^{14}CH_4$ and $^{14}CO_2$ detection in gas samples
- Shimadzu TOC-V$_{CSH}$ Total Carbon Analyzer for dissolved inorganic carbon and dissolved organic carbon and nitrogen quantification
- Agilent 6850 Gas Chromatograph with electron capture detector for nitrous oxide measurement

FACILITIES, EQUIPMENT AND OTHER RESOURCES

- Dionex DX-500 Ion Chromatograph for sulfate, chloride and other anion and cation analyses
- Hewlett Packard Liquid Scintillation Counter for measurement of radioactivity (^{14}C and ^{35}S) in liquid samples
- Agilent 1200 Series Liquid Chromatograph system for measurement of low molecular weight organic acids
- Glove Box for anaerobic sectioning and processing of soil cores
- Shimadzu Spectrophotometer for colorimetric analyses

Supplementary Document - Data and Information Management Plan

The goal of the PIE LTER data and information system is to provide a centralized network of information and data related to the Plum Island Ecosystems. This network provides researchers access to common information and data and protected long-term storage of their data. The centralized network makes data and information easily accessible to local, regional, and state partners and the broader scientific community. Researchers associated with PIE are committed to the integrity of the information and databases resulting from their research.

Access by the public and scientific community to data and information is provided by the website, http://pie-lter.ecosystems.mbl.edu. The website contains information on research, data, education and outreach, personnel and publications. Datasets are accessible via the PIE website data section and searchable using the LTER Network Information System (NIS) Data Portal. PIE maintains an Intranet site with archived datasets from which the PIE website is updated.

PIE information and data are stored on an MBL Microsoft Windows server with a level 3 RAID array that is backed up using CrashPlan PROe Server, an Enterprise level backup system. The PIE website (Drupal Content Management System) is managed on a Linux, LAMP system. The database and file system are backed up nightly. MBL researchers can directly access archived data on MBL's server and MBL provides software and network storage capability for backing up MBL researchers' individual computers. Non-MBL researchers have access to a secure FTP website at MBL for archival back up of their data (both unprocessed and processed).

Data Management and Design of Research Projects

Data management and design of research projects are 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 for PIE LTER. The rest of the information management team consists of: Anne Giblin (Lead PI), Joe Vallino (PI), Robert Pontius (PI), Jane Tucker (SRA), Liz Duff (Education) and research staff with computer programming expertise. The team has the necessary leadership, knowledge and technical expertise for creating and maintaining the PIE research information.
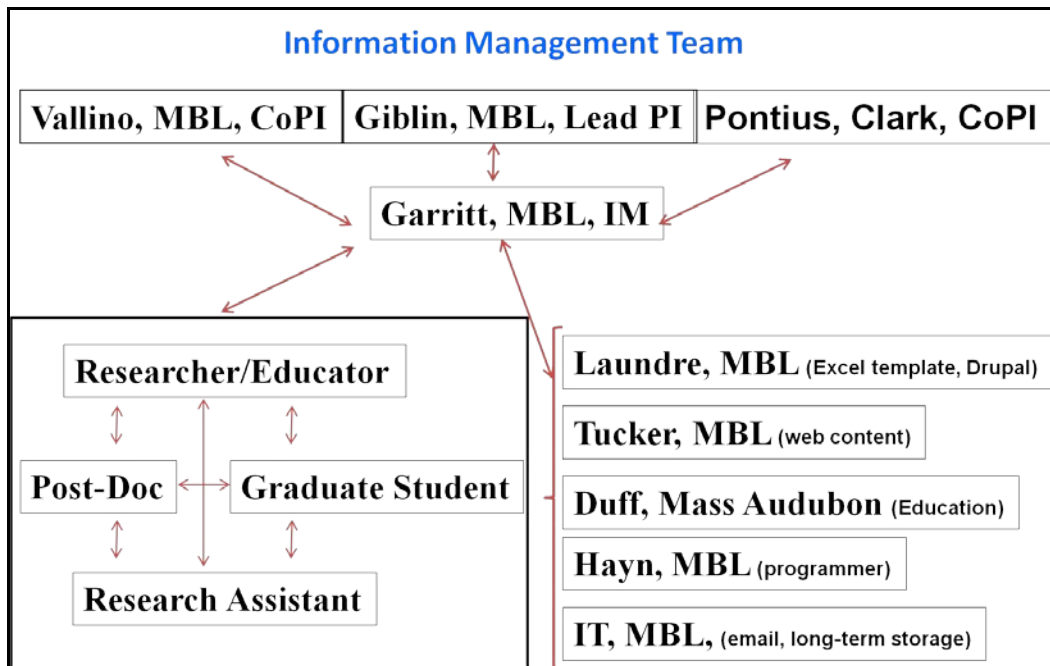
Supplementary Document - Data and Information Management Plan

Continuity of the system relies on the multi-person management team to provide experiential memory of the system. Garritt has been involved with the design and execution of many of the research projects, which allows for a smooth incorporation of data and information into the PIE database. Several meetings each year provide each researcher the opportunity to communicate with the PIE information management team regarding the design of the specific research project and subsequent incorporation of data and information into the PIE LTER database. Guidelines for the PIE Information System are available on the web, http://pie-lter.ecosystems.mbl.edu/content/information-management, and include Data Policies and Protocols, Description of Information Management and Data Submission documentation.

Contributions of Data to Database

Individual researchers are responsible for providing metadata and data via a PIE LTER Excel Metadata Template for each of the core research areas. Researchers on the PIE LTER are expected to follow the LTER Network data release policy defined on the LTER web page, http://lternet.edu/policies/data-access. Researchers using the facilities of the PIE LTER are expected to comply with the LTER policy and encouraged to make data available even if they are not funded by the LTER. Data files must include accompanying documentation files that completely describe the data. PIE currently uses a Microsoft Excel spreadsheet template for managing metadata and data. The Excel template provides utility for: 1) consistent metadata entry, 2) subsequent conversion via a visual basic macro to XML structured Ecological Metadata Language (EML 2.1.0) according to EML Best Practices for LTER Sites and 3) QA/QC checks for uploading to the LTER Network Data Portal. Individual researchers work with the data manager to properly format their data sets but ultimately are responsible for quality assurance, quality control, data entry, validation and analysis for their respective projects. 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 Annual Spring PIE LTER All Scientists Meeting. The PIE Executive Committee is responsible for dealing with researchers who do not submit data in a timely manner to the database. The Executive Committee reserves the right to withhold funding or restrict services and facilities to researchers who do not contribute their PIE-related data.

Data Accessibility and Timeliness

Researchers funded by the PIE LTER are required to contribute data to the PIE LTER database. 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 data sets for incorporation into the PIE LTER database. 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. Selected data (weather, water level and water quality) are made available in near real time to provide timely awareness of local conditions. PIE follows the data release policy for the LTER network that states:

"There are two types of data: Type I (data that are freely available within 2 years) with minimum restrictions and, Type II (Exceptional data sets, rare in occurrence that are available only with written permission from the PI/investigator(s))."

PIE strives to make datasets easily accessible to PIE LTER scientists, local, regional, and state partners and the broader scientific community. Datasets are available across the broad breadth of PIE research in the watersheds and estuary. We continue to have no registration requirements for either observing or downloading data from our website, which has resulted in seamless access to all PIE LTER data. PIE data downloads on our website are accompanied by a metadata document, which requests (based on the honor system) users of the data to notify the corresponding Principal Investigator about reasons for acquiring the data and resulting publication intentions (see PIE LTER Data Use Agreement.)

PIE contributes routinely to network databases of ClimDB/HydroDB, Personnel, Bibliography and Site DB. Contributions of data and metadata to the LTER Network Data Portal are an active ongoing process with 375 data sets currently available for the PIE site in the LTER Network Data Portal. We

continue to QA/QC additional data for EML 2.1.0 compliancy and upload to the LTER Network Data Portal.

PIE maintains a server at the Rowley Field station to manage streaming of telemetry data from weather, water quality and eddy flux remote stations. Near real time field conditions at PIE field sites are important to researchers planning field studies. Data such as tidal water level height, temperature and precipitation patterns and water quality are made available via UHF and VHF radio telemetry from Campbell data loggers in the field to a base station running Windows server at the Rowley Field station. Near real time images of the data are generated using Campbell RTDM (Real Time Data Management) software. For easy access, the imagery and data are accessible to researchers in a menu, Near Real-Time Weather and Water Quality on the front page of the PIE home page.

Accomplishments 2010 -2016

Our new upgraded website became operational in 2013. Upgrading the PIE website to a more modern, user friendly, functional website had been a major priority over the last several years. The current PIE website, http://pie-lter.ecosystems.mbl.edu, based on a Drupal content management system, provides a comprehensive and easily navigable interface through use of dynamic menus and search capabilities. The PIE website is a product of our Drupal Ecological Information Management System (DEIMS) collaboration with other LTER sites (SEV, LUQ, NTL, ARC, JRN,LNO), the MBL/WHOI Library and Encyclopedia of Life. The website will be further improved upon with our anticipated migration to a Drupal 7 version of DEIMS, https://drupal.org/project/deims, during the next funding cycle. In the open source community, Drupal 7 is more widely supported than Drupal 6 which will allow for standardization across the DEIMS collaborative.

A Google map module in Drupal has allowed us to provide a dynamic PIE domain map interface on our website for displaying research site/sampling locations which are linked to data sets associated with that site, PIE site data map. This feature has been especially helpful to researchers who are curious about the breadth of available data at particular locations throughout PIE LTER.
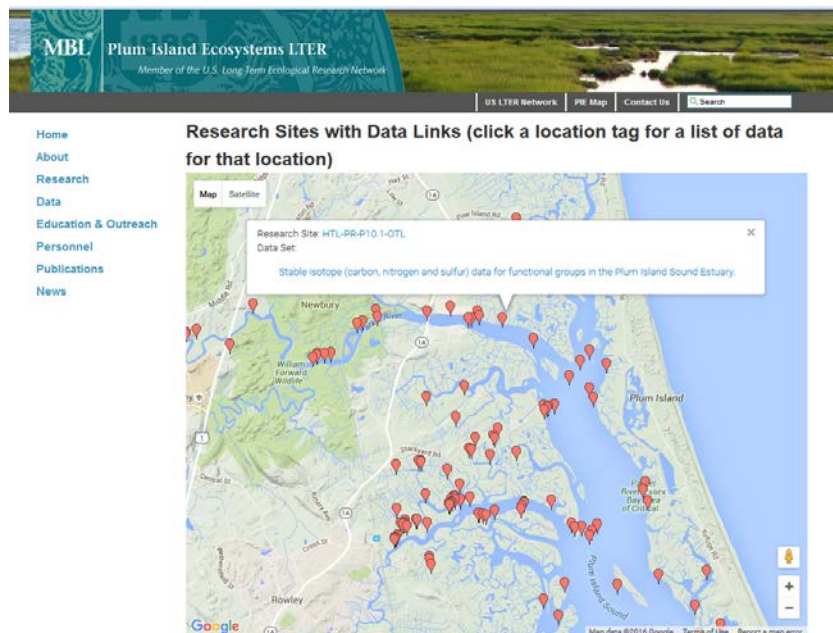
PIE prioritized improving data accessibility on the PIE website and in the LTER NIS. We have been updating metadata from EML 2.0.1 to EML 2.1.0 to provide high quality data and metadata for the PIE website and the LTER Network Data Portal.

PIE developed a script to convert our legacy GIS metadata from MS Word FGDC metadata to EML 2.1.0. Using the ESRI2EML script developed by the LTER IM community, PIE has converted Clark

University half-meter resolution land cover for all 26 towns in the PIE domain from ESRI metadata to EML 2.1.0. These high resolution data and high quality metadata are available in the LTER Network Data Portal. All PIE legacy GIS information is now EML 2.1.0 compliant and available in the LTER Network Data Portal. Clark University via PIE supplement funding installed an additional server on Clark's campus for storing and analyzing the half-meter resolution land cover data. The server also provides a full, regular, automated back up to a secondary location on Clark's campus.

During the past year PIE data have become available via collaboration with the Biological and Chemical Oceanography Data Management Office (BCO-DMO) on the [BCO-DMO website](#). BCO-DMO works with investigators to serve data online from research projects funded by the Biological and Chemical Oceanography Sections and the Division of Polar Programs Antarctic Organisms & Ecosystems Program at the U.S. National Science Foundation. PIE as an NSF-OCE funded LTER is excited that our data have become available to ocean science researchers on the [BCO-DMO website](#). The data links managed by BCO-DMO are derived from PIE uploads to the LTER Network Data Portal.

We expanded our Education and Outreach information on the PIE website to elaborate on the breadth of programs and initiatives undertaken by our Education coordinator Elizabeth Duff. The Schoolyard K-12 program continues to expand the breadth of curriculums which include: [Salt Marsh Science](#), [Lessoning Loosestrife](#), [Striped Bass](#), [Inland Fish and Warming Waters](#), and [Sea Level Awareness](#). PIE researchers also began involvement during 2015 with the Michigan State University NSF sponsored [Data Nuggets](#) activity. Elizabeth Duff leads [PIE's Data Nugget](#) involvement to inspire teachers and scientists to bring data from ongoing research into the classroom and take students through the process of science, from the inception of ideas to the analysis and interpretation of data.

Goals for the Next Funding Cycle

PIE plans to migrate our current Drupal website to a Drupal Ecological Information Management System (DEIMS) Drupal 7 version during the next funding cycle. The Drupal 7 DEIMS (DEIMS 7) version will allow PIE to have comparable software with other LTER DEIMS sites. DEIMS 7 includes improved views and searching capabilities. We currently have a DEIMS 7 development site and have successfully tested migration of data. We will be working on migrating and mapping existing web content to the development site in the next year.

An ongoing and never ending process is the pursuit of the goal of generating and ensuring high quality data and metadata that are easily accessible and searchable. PIE will continue to generate and upload data and metadata to the LTER Network Data Portal that meet the LTER community standard. PIE still has some older "legacy" EML 2.0.1 data and metadata that will be upgraded to EML 2.1.0. The EML congruency checker in the LTER Data Portal has greatly improved the QA/QC of metadata and sped up the process of generating high quality metadata.

PIE plans to collaborate in every way possible with the LTER Network Communications Office (NCO) and the currently undecided configuration of the LTER Network Information Management Office to ensure the goals of both organizations. PIE will provide data and IM expertise as appropriate for Synthesis Working Groups and continue to work with the LTER NIS to promote access to high quality data and metadata.

GOVERNANCE AND COORDINATION - Overall direction and management are provided by lead PI, Anne Giblin, and the executive committee. The executive committee has been reorganized to reflect leadership of the major program areas in our conceptual model of proposed research. The program coordinators are: Wil Wollheim (U. New Hampshire) - watersheds, James Morris (U. South Carolina) - geomorphology, Nathanial Weston (Villanova U.) - biogeochemistry, Linda Deegan (MBL) - consumers, and Joseph Vallino (MBL) - modeling. The executive committee also includes one rotator. Robert Pontius (Clark U.) remains on the executive committee as the rotator for the first year, followed by Jarrett Byrnes (U. Massachusetts Boston, UMB), a new member of the consumer group. Future rotators will be chosen by the Executive committee with a focus on individuals who are most likely to be future program coordinators. Giblin and one member of the executive committee attend the LTER network science council meeting and Giblin is currently on the LTER Executive Committee.

The executive committee is consulted on all financial matters and supplement requests, collects information for annual and final reports from other members of their program area, and facilitates transitions in leadership. The Executive Committee meets in person twice a year and by phone every 1-2 months. Coordinators keep all members of the LTER informed about activities and findings in their program area. Each program area holds regular meetings that bring together PIs, students, post-docs and research assistants. Often these meetings involve several groups meeting together, either formally or informally at the field station. Major research directions and strategic planning are discussed with all of the PIs and senior personnel involved in the LTER project and decisions are reached by consensus.

Each spring we hold a meeting of all scientists, post-docs, students and research assistants associated with the LTER. All personnel working on PIE LTER-related projects are invited to attend and present their findings. At our annual meeting we summarize the results of individual program areas, synthesize across disciplines, and plan the research program for the coming year. Graduate students present theses ideas and participate in the planning for the upcoming field season. We also encourage representatives of governmental agencies and NGOs working in the area and teachers working with our education program to attend the annual meeting and give presentations on their work.

ENCOURAGING NON-LTER SCIENTIST PARTICIPATION AND COORDINATION - We have been able to broaden participation by writing grants with non-LTER investigators. We encourage non-LTER scientists and students to work at PIE and whenever possible assist them with site access, housing and computer facilities, and data and maps to help plan their research. Investigators coming for short periods of time are put in contact with the PI or research assistant / field technician most able to assist them. We actively help scientists from other LTER sites find study locations for comparative studies. Scientific and logistic coordination with non-LTER scientists is achieved through our annual meeting, and by interactions with PIE LTER investigators. Our program coordinators serve as the key points of contact for long-term projects.

EDUCATION and OUTREACH - PIE has an education and outreach committee led by Robert Buchsbaum (Mass Audubon) that includes Elizabeth Duff (Mass Audubon), Giblin, Weston and David Johnson (Virginia Institute of Marine Science). Duff serves as our education coordinator and is included in all discussions that involve education and outreach. She also spearheads the Perennial Pepperweed Eradication Program, which is a collaboration between Mass Audubon, the Parker River National Wildlife Refuge (PRNWR), and a number of other regional partners. It involves hundreds of volunteers including those from the Gulf of Maine Institute (GOMI). Duff interacts with PIE scientists to produce courses for teachers on topics such as climate change impacts on marshes and striped bass. She also facilitates scientist and teacher participation in educational activities at the LTER network level such as the "Data Nuggets" program. Other PIE scientists take responsibility for specific programs. Giblin chairs the board of GOMI, which is working to launch a new initiative to increase diversity (described below). Deegan frequently supervises high school interns from the Governor's Academy, a local high school.

Each year PIE scientists have the opportunity to request an REU from the two provided to the LTER. In addition, we normally have 3-4 other undergraduates and several graduate students in residence. At the end of the summer we hold an all-day meeting where graduate and undergraduate students can present their work to PIE scientists and local agency managers.

Our outreach activities continue to grow, as local and regional interest in our research increased dramatically after Hurricane Sandy (2012) and Nor'easter Nemo (2013) caused substantial erosion along the coast and flood damage in the watersheds. Giblin and Morris are advising Massachusetts Coastal

Zone Management on wetlands issues and coordinate with regional science and management groups interested in coastal sea-level rise. Wollheim is our primary contact with both the Ipswich and Parker River watershed associations and these groups have volunteers for our sampling programs.

Most PIs now take active roles in outreach and collaboration. Buchsbaum plays a major role coordinating with government agencies and NGOs in the area. He coordinates between PIE, the PRNWR and Mass Audubon to assemble regional bird data which is posted on the PIE site and represents PIE on a consortium of government and NGO groups working on river restoration. Giblin leads most interactions with PRNWR (site of our eddy flux towers), and with Essex County Greenbelt Association, a local land trust. Deegan and Mather work with sports fisherman's associations, local and state fisheries management agencies, and regional groups interested in striped bass and herring. Vallino coordinates PIE modeling efforts with other regional modeling efforts and is active in a network of researchers developing the MEP concept for ecosystem studies.
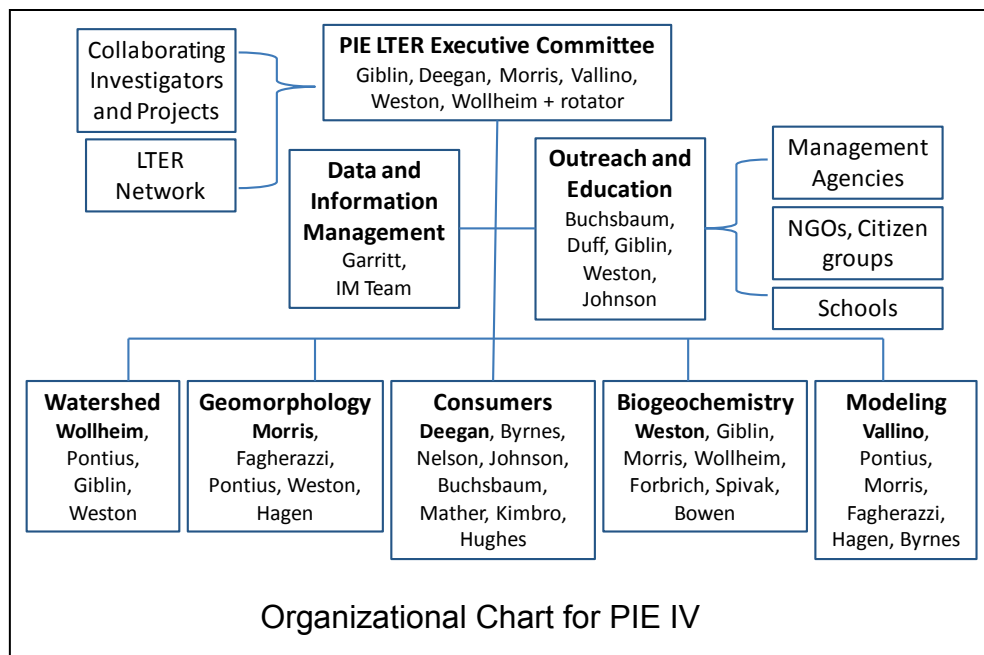
INCREASING DIVERSITY - At the K-12 level we have increased the number of minority students participating in the program by adding the Collins Middle School in Salem, MA. Our undergraduate activities are advertised widely. We now get many more women applicants than men but still have trouble recruiting minority students. We have increased our coordination with U. of Chicago and the MBL-Semester in Environmental Science program, which have active minority recruiting programs. In addition, our connections to UMB, have helped us recruit minority applicants. UMB serves the largest minority population (44% following federal definitions) of any public research university in New England, and fully 48% of UMB's undergraduates were first in their families to attend college. At the graduate and post-graduate level, the PIs use list-servs set up by scientific societies and their own institution's HR departments to assure a wide distribution of position announcements and take advantage of the minority recruiting efforts of professional societies (e.g., AFS, ESA, ASLO, ASCE). Community college students often receive very little hands-on training in STEM fields and therefore, rarely choose a STEM field for a career. Our newest initiative, described in the Education and Outreach section of the proposal, is a joint effort with Middlesex Community College and GOMI to provide undergraduates with paid internships with PIE scientists that provide academic credit.

PI ADDITIONS AND ROLES OF OTHER SENIOR PERSONNEL - We are adding several early to mid-career scientists to the senior personnel of the PIE LTER. Byrnes' background is in quantifying the network topology of food webs and examining how those topological properties might contribute to the stability and resilience of food webs. He is also interested in understanding the relationship between community structure and ecosystem function. Byrnes will assume responsibility for coordinating the long-term monitoring program of marsh and creek invertebrates and nekton. He will work closely with James Nelson (U. of Louisiana Layfette) who uses stable isotopes to determine trophodynamics. Two new scientists from Northeastern University, Randall Hughes and David Kimbro, will add additional depth to community ecology for PIE. Hughes is interested in understanding the interactions between the abundance and identity of plant species, the genetic make-up of individuals, and the ecosystem services that they provide. She has conducted reciprocal transplant experiments of *S. alterniflora* from multiple sites along the Atlantic coast using PIE as her northern-most site. Kimbro's interests include a broad range of issues in population dynamics, community ecology, invasion biology, ecosystem science, and coastal oceanography. At PIE, he has a graduate student studying the ecology of blue crabs along a latitudinal gradient N and S of Cape Cod, and another project examining how large accumulations of wrack from the invasive plant *Phragmites* will affect saltmarsh plant and animal community dynamics. Two young biogeochemists have been added. Inke Forbrich (MBL), a former post-doc, runs the eddy covariance tower and is working on C balances in marshes, and Amanda Spivak (Woods Hole Oceanographic Institution) is working on C cycling in marsh ponds. Scott Hagen (Louisiana State U.) brings added strength to modeling hydrodynamics and geomorphology.

In 2012 we brought on a number of early to mid-career scientists who are now taking on greater roles in the project. Weston replaces Charles Hopkinson as leader of the biogeochemistry program. Sergio Fagherazzi is a geomorphologist from Boston University who also works at VCR LTER. His participation facilitates interactions on sediment modeling between the two LTERs. Bowen (now Northeastern

Organizational Chart for PIE IV

University) brings microbial expertise to PIE. She works with Deegan on the TIDE experiments and has a student working with Giblin and Vallino. Johnson will lead the work on the fiddler crab expansion (H3.2) as well as continue to provide expertise in invertebrate biology.

PI and LEADERSHIP TRANSITIONS - A number of PIE PIs will either end their involvement at the end of PIE IV, or at least step back from leadership roles. Based upon the experience of other sites we believe that a 2-3 year period of transition, with overlap, is optimal for changing leadership of program areas and especially critical when changing the lead PI. This allows the new PI to become very familiar with all aspects of the program and with local partners. We expect to determine who will take on lead-PI status for the next LTER cycle by the time of our 3-year review. Deegan and Morris will relinquish leadership roles near the end of PIE IV and their successors will be determined by year 3 or 4 of PIE IV. We have a number of outstanding new scientists who are at a stage in their career where they will soon be able to take on greater leadership roles.

ADVISORY GROUPS - PIE III did not have a permanent standing advisory board. Instead we invited outside experts to our annual meetings. In PIE IV we will assemble a rotating advisory committee of 3 people. The committee will attend our annual meetings and provide advice on overall LTER progress, coordination, and topics of Executive Committee concern.

MANAGEMENT OF FIELD FACILITIES -The PIE LTER manages two field facilities, the Rowley House and Marshview Farm. Marshview is owned by the MBL and sleeps 14. An MBL post-doc or research assistant is in residence at Marshview throughout the field season to provide on-site supervision. The Marshview facility is supplemented by the Rowley Field House, which is rented from Essex County Greenbelt. This facility is reserved for short term stays. It provides dock facilities for 3 boats to give us easy and immediate access to the water and provides walking access to many of our field sites. Researchers reserve space at the field sites at our annual March meeting. After LTER slots have been reserved, both facilities are available to other collaborating projects, and other researchers affiliated with federal and local partners as space allows. Outside investigators are charged a very small fee ($50/week) which is often waived for students. In the last years housing facilities were at capacity during the summer months. The Marshview facility was improved in 2014 by the addition of a new lab (~1,300 sq ft). The benefits from this addition were immediate. Before, lab space was so limited that groups had to plan their trips so they did not overlap. The additional space allows for much more group interaction, and more efficient use of field time.