

PROJECT SUMMARY

Intellectual Merit: The Plum Island Ecosystems (PIE) LTER has, since its inception in 1998, been working towards a predictive understanding of the long-term response of coupled land -estuary- ocean ecosystems to changes in three drivers: climate, sea level, and human activities. The Plum Island Estuary-LTER includes the coupled Parker, Rowley, and Ipswich River watersheds, estuarine areas including a shallow open sound, and extensive tidal marshes. PIE is connected to the Gulf of Maine in the Acadian biogeographic province, which is a cold water, macrotidal environment that is geographically and biologically distinct from coastal ecosystems to the south of Cape Cod, Massachusetts.

Over the next four years we will build upon the progress we have made in understanding the importance of spatial patterns and connections across the land-margin ecosystem. **Our overarching goal is 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 control ecosystem processes, is both a fundamental science question and a critical management question. During the remainder of PIE III we will continue to address the role of temporal change and variability in climate, sea-level rise and human activities on ecological processes in our long-term monitoring but we will also initiate new activities that examine spatial arrangements and connectivity. Our research questions are focused around two themes:

- 1) *What controls the spatial arrangements and connectivity between ecological habitat patches in the coastal zone?*
- 2) *How do the spatial arrangement and the connectivity between ecological habitat patches in coastal watersheds and the estuarine seascape influence ecological processes?*

To address our goal we will: 1) Quantify recent changes in spatial arrangements and connectivity in the watershed and estuary and investigate their drivers. 2) Supplement our long-term monitoring with additional measurements in the watershed and estuary to understand how ecosystem processes are influenced by different spatial arrangements and connectivity. In the watershed these include areas where the river network has been modified by suburbanization and beaver dams. In the estuary we will examine feedbacks between form and function in contrasting areas that appear to be responding very differently to sea-level rise; in one case maintaining the marsh platform and in another losing marsh area, forming ponds and transitioning to a lower elevation. 3) Continue existing and add new large scale manipulative experiments to increase mechanistic understanding of ecological processes in various critical land and seascape patches and their responses to drivers. 4) Develop and apply models to understand how biogeochemical and trophic processes emerge at broader scales in a spatially complex coastal environment.

Long-term data collection, however, will remain a central activity as many of our hypotheses as to the importance of geomorphic change to ecosystems processes have come from our observations that spatial arrangements and their connections at PIE are rapidly changing, on the time scale of decades. Further, we continue to expand efforts to understand how management decisions are influenced by both geomorphic and ecosystem changes. These interactions and feedbacks are important drivers of change at PIE and as a consequence we have increasingly integrated human activities within the PIE conceptual framework.

Broader Impacts: Our K-12 schoolyard program, “Salt Marsh Science”, serves over 1,000 students in grades 5-12 in ten schools and we hope to continue to expand this into more schools. Our education coordinator, Ms. Duff, has co-founded an effort to eradicate perennial pepperweed that involves over 1000 students and adults. This effort has attracted regional attention and partners. We serve college undergraduates through internships, research projects and field trip. REU opportunities for undergrads exist through the PIE-LTER, the NSF funded Clark “HERO” program, the MBL-Brown partnership, and the U. of New Hampshire. We will continue our collaboration with the MBL Brown IGERT Program, where graduate students are exploring the intersection between modern genomics and ecosystems science. Outreach is a very important part of our mission and includes inter-LTER efforts and participation in the MBL’s science journalism program. We have close connections with the nearly all of the management agencies and NGOs in the region and serve on many advisory boards. All data collected by the PIE LTER are centralized and made available through our web site.

SECTION 1: RESULTS OF PRIOR SUPPORT

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Goals of the Plum Island LTER

The Plum Island Ecosystems (PIE) LTER is an integrated research, education and outreach program whose goal is to develop a predictive understanding of the long-term response of watershed and estuarine ecosystems at the land-sea interface to changes in three key drivers: climate, sea level and human activities. The PIE-LTER was established in 1998. Our principal study site is the Plum Island Sound estuary and its watersheds located in eastern Massachusetts north of Boston (Fig. 1.1).

While our overall goal has not changed over the past 14 years, our conceptual framework for the LTER has evolved. PIE I and II focused on the *temporal* variability in climate, sea level and land use change as external drivers and examined how ecosystems responded to these forces. Research during PIE I and II showed that ecosystem responses were strongly influenced by hydrology and were mediated by the *spatial arrangement and connectivity* between patches in the coastal landscape. During PIE II it also became clear that these spatial arrangements and their connections were rapidly changing, on the time scale of decades. At the end of PIE II, and transitioning into PIE III, we began to investigate the mechanisms leading to changes in spatial arrangements and connectivity and the ecosystem response. We also observed that humans were making management decisions in response to ecosystem changes. These interactions and feedbacks are important drivers of change and required that we integrate human activities within the PIE conceptual framework rather than viewing humans as an external forcing function. Below we highlight major findings of the last six years. This section includes only PIE publications. Our ten most significant papers since 2006 are in boldface.

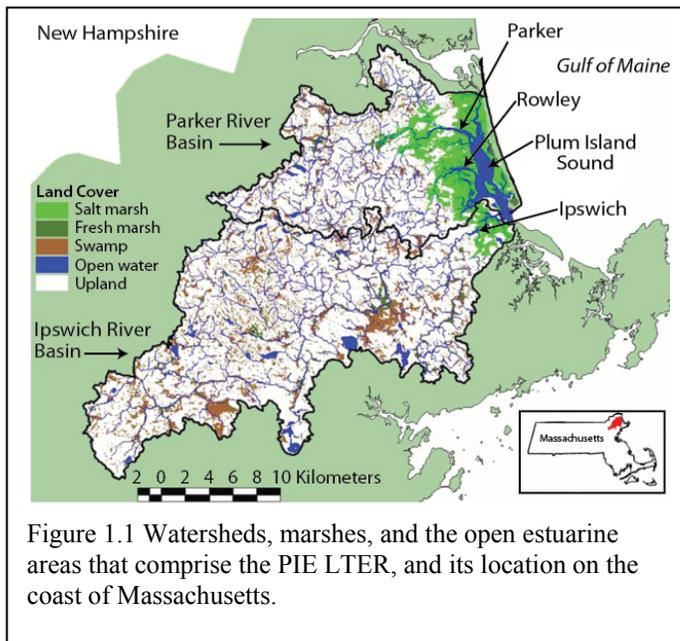


Figure 1.1 Watersheds, marshes, and the open estuarine areas that comprise the PIE LTER, and its location on the coast of Massachusetts.

HYDROLOGY AND HYDRODYNAMICS

Human impacts of suburbanization on the hydrologic cycle have been large at the scale of small streams, but muted for the entire basin because of water diversions and regional changes in climate. Suburbanization has altered hydrologic flux timing and magnitude in PIE watersheds through pumping of groundwater, through cross basin transfers, (Williams et al. 2004; Williams et al. 2005; **Claessens et al. 2006**), by storm water management, and by an increase in impervious surfaces (Pellerin et al. 2008; Fig 1.2). By the early 2000s the average net diversion of water reached 20% of annual river runoff. This large diversion masked the underlying trend of increasing precipitation and impervious runoff with the result that average *annual* runoff has not changed at the whole watershed scale (**Claessens et al. 2006**).

There have been significant hydrologic impacts from water diversions at the local scale, especially during summer, due to the spatial heterogeneity of both land-use patterns and withdrawals (**Claessens et al. 2006**; Schneider and Pontius 2001; Polsky et al., 2012). Spatial heterogeneity influences the timing and distribution of discharge and the watershed's ability to buffer the impacts of suburbanization on downstream ecosystems (Wollheim et al. 2008a; Stewart et al. 2011). Local water shortages led to a decline in water withdrawals after 2004 and to residential water-use restrictions within towns. Water-use restrictions are increasing in duration and frequency and appear to be associated with not only local homeowner and town land- and water-use practices but also state-level policies (Polsky et al. 2009; **Hill**

and Polsky 2005, 2007; Guha 2009). These “suburban droughts” are thought to be driven by summer lawn irrigation. Our surveys and interviews with homeowners reveal that intensive yard care practices, such as irrigation and fertilizer application, occur less often in the PIE watersheds than expected based upon other study areas (von Trapp 2010; Harris et al., 2012). We are comparing these qualitative findings to other LTER sites including CAP, BES, and FCE (Harris et al., in review). Our statistical analyses of the land use-water link suggest that (1) PIE lawn cover patterns may not be as strongly linked to lifestyle patterns as at BES (Giner et al., in review); (2) an innovative residential water pricing scheme has reduced the importance of lawn cover on local water use (Krahe 2012); and (3) even though recent price changes have reduced residential water-use, in the coming decades water-use may exceed mandated limits (Runfola et al., in review).

Improved modeling of PIE estuarine circulation We have developed a 3D circulation model of the PIE domain using FVCOM (Finite-Volume Coastal Ocean Model) that we can couple to sediments transport and biogeochemical models. The model has also yielded new insights on the importance of connections to the Merrimack River (MR). Model simulations suggest there is a significant exchange of water between the MR and PI Sound, and this was confirmed through field measurements (Zhao et al. 2010). This research indicates that coastal models cannot simulate large rivers as just point sources, but must also include any associated marsh platforms due to changes in tidal dynamics they induce.

BIOGEOCHEMICAL CYCLES

Human activities dominate the nitrogen cycle of PIE watersheds, however, both land use intensity and development location determine rates of ecosystem N removal. As is increasingly the case for coastal zones worldwide, human N input via food/waste and fertilizer dominates the contemporary N budget of PIE watersheds (Williams et al. 2004). Despite relatively high inputs, our watersheds export a lower percentage of N inputs than other urbanized watersheds in the northeastern United States and more closely resemble the highly retentive watersheds in the southeast. Low percent export occurs because the most urbanized areas are in distant headwaters, and because riparian and floodplain wetlands are abundant, allowing for more efficient cumulative removal during transit downstream. The high N retention in PIE watersheds demonstrates the critical importance of spatial topology as a determinant of human impacts on the coastal zone.

Increased suburbanization, however, does cause a decline in N retention. Impervious surfaces result in fewer biologically active areas in suburban catchments and in shorter residence time as storm water is shunted directly to streams. This effect is exacerbated during wet years. Experiments in headwater streams demonstrate that denitrification is significant, but that its relative magnitude declines as loading increases (i.e. efficiency loss; Mulholland et al. 2008; Thouin et al. 2009). However, the system as a whole may function to compensate for some of these losses. Modeling results indicate that stream networks remain extremely capable of removing N inputs, particularly under lower flows (Wollheim et al. 2008a), when specific hydraulic and geomorphic conditions are met (**Wollheim et al. 2006**). Both exchange with transient storage zones during routing and the abundance of floodplain wetlands appear to enhance removal efficiency (Briggs et al. 2010; Stewart et al. 2011). Complex spatial and temporal patterns demonstrate the value of integrating connectivity between rivers and highly active zones (“hot spots”) into network models (Wollheim et al. 2008a; Helton et al. 2011).

Estuarine aquatic respiration is supported primarily by marsh organic matter while terrestrial organic matter plays a relatively small and local role. There are strong spatial gradients in metabolism along the length of PIE estuaries and overall PIE estuaries are net heterotrophic (Vallino et al. 2005). Carbon from the watershed can only support heterotrophic demands in the upper 5 km of the estuary. Distributions of naturally occurring ^{13}C and ^{14}C isotopes show that the remaining respiration cannot be met by the erosion of marsh peat (Raymond & Hopkinson 2003). As a result, mass balance requires a substantial input of carbon from marsh grasses to sustain estuarine heterotrophy. Creek bank porewater is rich in organic carbon and high porewater drainage rates of this C-rich water (Gardner & Gaines 2008) contribute to estuarine aquatic respiration. However, by comparing total water column and benthic respiration to free water measures of respiration, we found much of the apparent estuarine respiration in water occurred on

the marsh proper and was exported as inorganic C. Understanding the topology of C production and metabolism enhances our understanding of how marsh derived C supports higher trophic levels.

Spatial and temporal variability of nitrogen cycling and N removal in PIE estuaries depend on hydrology, N loading, and elevation. Nitrogen removal within marshes and estuaries is an important ecosystem service but rates are quite variable in time and space and difficult to measure (Hopkinson & Giblin 2008). In the subtidal areas of PIE, estuarine N dynamics are strongly controlled by temporal and spatial patterns of water residence time, salinity, and N inputs. We observe high summer denitrification rates in the upper Rowley estuary (Fig. 1.1) where water residence times are short and N uptake is dominated by benthic algae (Tobias et al. 2003a). In contrast, in the upper Parker estuary, where summer residence water times are often long, we find denitrification rates are usually low and N cycling is regulated by salinity changes both seasonally and inter-annually (Weston et al. 2010; **Giblin et al. 2010**). Rates of sediment ammonium release and dissimilatory nitrate reduction to ammonium (DNRA) increase with salinity while denitrification decreases. As salinity rises over the summer, NH_4^+ is released from sediment particles through ion exchange (Weston et al. 2010), the efficiency of nitrification decreases (**Bernhard et al. 2007, 2005**), and DNRA is favored over denitrification (**Giblin et al. 2010**). The net result is that more N is available to primary producers. These findings suggest that estuaries which experience very variable salinity regimes may be less efficient in removing watershed N inputs.

At higher elevations, where marsh grass is present, plants exert a strong control over N cycling. Our new denitrification technique for vegetated sediments showed that denitrification occurs throughout the *Spartina patens* rhizosphere, contributing substantially to overall N removal in marsh sediments (Koop-Jakobsen & Giblin 2009a; 2010). DNRA is often as important as denitrification as a nitrate sink, whereas anammox is unimportant (Koop-Jakobsen & Giblin 2009b, 2010; Uldhal 2011). By making these measurements in fertilized creeks (TIDE, **Deegan et al. 2007**) we were able to show that although both DNRA and denitrification increase with increased nitrate loading (Koop-Jakobsen & Giblin 2010), the efficiency of N uptake decreases with N concentration (Drake et al. 2009). We also found that the narrow *S. alterniflora* creek banks appear to be "hot spots" of N removal (Drake et al. 2009).

New approaches to modeling estuarine biogeochemistry We have been developing a metabolic approach (Vallino et al. 1996; Vallino 2003) that relies on the principle of maximum entropy production, MEP, to predict rates of specific biogeochemical reactions in ecosystems. The MEP approach is a powerful way to investigate ecosystem biogeochemistry, although there are still theoretical challenges to be addressed. We have been developing theory and models to describe how microbial biogeochemistry change as a function of resource and energy availability, based on non-equilibrium thermodynamic principles alone. This new perspective represents a paradigm shift from "microbes determine the biogeochemistry" to "chemistry controls which microbes will be present". Our analysis indicates that abiotic reactions maximize entropy production instantaneously, while living systems maximize entropy production integrated over time based on temporal strategies they have acquired via evolution. Temporal strategies can allow biotic systems to outcompete abiotic processes (**Vallino 2010**). We are currently exploring the implications of using MEP in a complex spatial environment (Vallino 2011).

SPATIAL PATTERNS AND CONNECTIONS

Marshes have "tipping points" beyond which they cannot keep up with sea-level rise. Salt marsh primary production is strongly tied to changes in sea level. When marshes are perched high in the tidal frame, as they are at PIE, the relative marsh elevation is above the optimum for marsh grass growth. Consequently, in years when sea level is anomalously high, primary production responds positively. Sea level also varies over an 18.6 year period (lunar nodal cycle) which changes the amplitude of the tides by about 5 cm. Our research has shown that this change in the flooding duration is sufficient to alter biogeochemistry and primary production at PIE, South Carolina and other locations.

We have developed a model that explains how marsh seascapes maintain equilibrium with sea level (Morris et al. 2002; Mudd et al. 2004; Morris 2006; Morris 2007a) through feedbacks among marsh vegetation, sediment supply and relative sea level. These feedbacks allow the marsh to maintain an equilibri-

um elevation by changing rates of sediment accretion (Morris et al. 2002; **Mudd et al. 2009**; Mudd et al. 2010). The feedback loops result in an equilibrium elevation of the marsh that decreases as the *rate* of sea-level rise increases, and the productivity of the marsh increases to a limit with the *rate* of sea-level rise. Beyond that limit, marsh productivity and accretion will decline with further increases in sea level, leading to marsh disintegration. Based upon current rates of sediment supply, we predict that PIE marshes will transition to a lower equilibrium elevation as the rate of sea-level rise increases (Kirwan et al. 2011). Some high marsh at PIE will remain given that we observed areas of high marsh that appear to be maintaining their elevation as a consequence of cannibalization (Wang 2008) i.e. eroded peat from the marsh edge is deposited on the remaining surface. The model we have developed is being widely used to predict how marshes will respond to sea level rise and changes in sediment inputs.

Higher trophic levels, such as fish, rely on seascape configurations that create ‘hot spots’ of energy transfer up the food web. At small scales, mummichogs (*Fundulus*) rely on foraging “hot spots” determined by hydrology and demonstrate the greatest growth where the marsh floods frequently, thus providing greater access to high quality prey (Logan et al. 2006; Haas et al. 2009). At larger scales, striped bass, a top predator, develops two distinct feeding groups—one specializing in feeding on marsh-dependent species such as mummichogs in large tidal channels and one specializing in pelagic fish in the open bay (Pautzke et al. 2010; Ferry & Mather 2012). This specialized behavior may allow them to become more efficient predators, potentially increasing their top-down control on prey such as mummichogs. Understanding the role of striped bass in regulating mummichogs requires that we understand the regional scale dynamics of highly migratory striped bass. Using acoustic tags (funded by supplements) in conjunction with acoustic receivers along the Atlantic seaboard, we have discovered that 65% of PIE striped bass (ages 4-6) winter in Delaware Bay and over 60% return to PIE the following year (Mather et al. 2009, 2010). This demonstrates that northern and southern estuaries along the Atlantic seaboard are linked by fish migration.

Understanding future spatial patterns in land change processes requires new methods of analyzing maps. We have developed new methods in GIS to gain insight into land change processes (Pontius & Connors 2009). We have shown how a common measurement of map comparison, kappa, is flawed, and have proposed a better method that mathematically separates the assessment of the quantity of each category versus the spatial allocation of each category (Pontius & Millones 2011). Pontius & Neeti (2010) show that a predictive model of land-change in PIE produces various future projections that are not meaningfully different, given the uncertainty in the model. This has led us to take a scenarios approach that engages local stakeholders in a different type of modeling designed to enhance the conversation among scientists, stakeholders, and policy makers, without engaging in prediction per se. Aldwaik & Pontius (in press) have developed other new methods to measure the degree to which the statistical patterns of land change are stable over time. The inter-LTER project, Maps and Locals (MALS), uses the methods of Aldwaik & Pontius (in press) to compare land change across LTER sites. We have also developed methods to consider the accuracy of the maps and its implications for our measurements of land change (Pontius & Li 2010; Pontius & Petrova 2010).

Return of beaver is altering spatial arrangement and connectivity of streams with impacts on biogeochemistry and fish communities. Recently, beaver populations have dramatically increased in PIE watersheds, greatly altering stream channels. We applied ecological theory on heterogeneity to test whether beaver dams alter fish biodiversity and found that beaver dams resulted in increased native fish biodiversity at both local and watershed scales (Smith 2011; Smith & Mather in review).

CONTROLS ON SALT MARSH FOOD WEBS

Bottom-up control by nutrients is accentuated by the reduction of a key top consumer species in salt marshes. A large-scale experiment to quantify the effects and interactions of bottom-up (increased nutrients) and top-down (reduced abundance of a key consumer, mummichogs) controls shows that the ecological role of mummichogs varies across the landscape and that species behavior plays a significant role in structuring the salt marsh food web (**Deegan et al. 2007**; Fleeger et al. 2008; Johnson & Fleeger 2009;

Johnson et al. 2009). Contrary to the aquatic trophic cascade hypothesis, lower abundance of mummichogs in marsh creeks leads to a greater response of algae to increased nitrogen supply (Deegan et al. 2007). This suggests that the mummichog operates as an herbivore in areas of high algal productivity. In the detrital-based food web on the marsh platform, however, mummichogs exert strong top-down control on amphipods that function as litter shredders (Johnson et al. 2009; Galván et al. 2008). Fish reduction increased amphipod abundance 3-fold, potentially accelerating detrital decomposition and N cycling (Johnson 2011). Reductions in mummichogs induced a behavioral shift in grass shrimp: causing them to change foraging location and trophic level (herbivore to secondary consumer), functionally replacing mummichogs as predators in creeks. Shifts in behavior and trophic roles have altered the creek food web to more algal support and increased overall animal abundance (Galván et al. 2011). Hence, animals can alter their behavior sufficiently to become the equivalent of a new functional species resulting in substantially different food webs and energy flow.

Top down control by direct grazing on salt marsh vascular plants is minimal in PIE marshes. Top-down control of vascular plants by grazing, while important in some marsh systems, is minor at PIE. *Spartina* shows little evidence of grazing (Johnson & Jessen 2008), vascular plant grazers are not abundant and have not increased in response to any experimental manipulation (Johnson & Fleeger 2009), and the grazing species implicated in top-down control in other locations are not present at PIE.

Salt marsh food webs are resilient to large reductions in plant and detrital biomass. Based on long-term detrital removal experiments via haying (Buchsbbaum et al. 2009), we found that the removal of large amounts of aboveground biomass, had no effect on the abundances of intermediate trophic levels, fish or breeding birds, and only minor effects on the food web. Vascular plant diversity did not change. Benthic algal standing stock temporarily increased after haying; however the most abundant intermediate trophic level organisms (e.g., *Orchestia*, *Palaemonetes*) remained dependent on vascular plant organic matter. Our results differ from those of heavily grazed grassland LTER sites. We attribute this to the relatively lower intensity of biomass removed by marsh haying compared to grazing in grasslands.

CROSS-SITE AND SYNTHESIS ACTIVITIES Cross site activities have been central to PIE-LTER and include joint field measurements (e.g. Mulholland et al. 2008, Findlay et al. 2011, Hall et al. 2009), synthesis and modeling activities (e.g. Helton et al. 2011) and graduate student cross site training. The critical role of spatial heterogeneity across river systems was demonstrated using models developed at PIE that were then applied at broader spatial scales (Wollheim et al. 2008b; Beaulieu et al. 2011). Our models were also used to assess the importance of N₂O emissions from streams at the global scale (Beaulieu et al. 2011). The importance of watershed and estuarine processing and production of carbon to the delivery of carbon to the ocean was described in **Battin et al. (2008)**, while the implications of more local C budgets were explored in Raciti et al. (2012). Bain et al. (in press) explored legacies in material fluxes in watersheds across the LTER network. We produced a synthesis of marsh nitrogen cycling (Hopkinson & Giblin 2008) and have been active in evaluating denitrification methods (Groffman et al. 2006) and training students in these methods. Polsky and Pontius have been leaders or co-leaders in several cross-site social science initiatives made possible with supplementary funds (Chowdhury et al. 2011; Harris et al. 2012). We have contributed to efforts to understand how urbanization and pollution impact ecosystems (Grimm et al. 2008) and how an ecosystems services approach can be used to improve management (Farber et al. 2006). **Hopkinson et al. (2008)** led an effort to understand how sea-level rise and hurricanes will impact estuarine and upland coastal ecosystems. Mather and Deegan have been leading efforts to synthesize information on striped bass migration using acoustic tag data.

DEVELOPMENT OF HUMAN RESOURCES AND OUTREACH Our K-12 schoolyard program, “Salt Marsh Science”, is directed by Elizabeth Duff of the Massachusetts Audubon Society who recently won the “Massachusetts Marine Education of the Year” award. The program serves over 1,000 students in grades 5-12 in ten schools. Duff also has co-founded an effort to eradicate the invasive perennial pepperweed involving over 1000 students and adults. College undergraduates are served through internships, research projects and field trips. Since 2006, 61 students have carried out research projects at PIE

through the NSF funded Clark University Human-Environment Regional Observatory (HERO) program. Twelve post-doctoral investigators and 35 graduate students have been involved in PIE research since 2006. This year, as part of the MBL Brown IGERT Program, graduate students sampled at PIE and learned to apply next generation sequencing techniques to approach ecosystem questions. Outreach is a very important part of our mission and includes inter-LTER efforts and participation in the MBL's science journalism program. We have close connections with nearly all of the management agencies and NGOs in the region and serve on many advisory boards. We have developed an interactive marsh equilibrium model for managers and students. (More details are provided in Section 3.0.)

SECTION 2: PROPOSED RESEARCH

2.1 INTRODUCTION

The Plum Island Ecosystems (PIE) LTER has since its inception in 1998 been working towards a predictive understanding of the long-term response of coupled land -estuary- ocean ecosystems to changes in climate, sea level, and human activities. Coastal ecosystems at the land-sea interface are a dynamic ecotone between continents, oceans and the atmosphere. At the global level, estuaries and ocean margins play a key role in the transport, transformation, burial and exchange of water, sediment, organic matter and nutrients between the land, sea, and air (McKee 2003; Seitzinger & Harrison 2008; Battin et al. 2008). At the regional and local level, coastal ecosystems are highly valued by people and the site of some of the world's most intense population growth and activity (Scavia & Bricker 2006; Barbier et al. 2011). The increasing human use of coastal watersheds, coupled with climate change and sea-level rise, alters the ways in which materials and energy are transformed, as well as the vulnerability of people living in the coastal zone. However, the magnitude, and even the direction that these changes will take are not well understood. In turn, changes in the functioning of coastal systems will have important consequences for the people who value these ecosystems for food, recreation, storm protection, and other ecosystem services.

The Plum Island Estuary-LTER includes the coupled Parker, Rowley, and Ipswich River watersheds, estuarine areas including a shallow open sound, and extensive tidal marshes (Fig.1.1). PIE is connected to the Gulf of Maine in the Acadian biogeographic province, which is a cold water, macrotidal environment that is geographically and biologically distinct from coastal ecosystems to the south of Cape Cod, Massachusetts. Plum Island is the largest salt-marsh dominated estuary remaining in New England. In addition to supporting major commercial and recreational finfish and shellfish fisheries, the region is a world-renowned habitat for migratory birds.

Like most coastal areas worldwide, the area has experienced many human-driven changes. The watersheds were largely deforested by early European colonists, and then reforested as agricultural fields were abandoned in the late 1800s. Since 1950, there has been a loss of forest cover as population increased and suburban areas expanded rapidly (Schneider & Pontius 2001). With suburbanization, human use of water increased, concurrent with changes in natural patterns of precipitation and evapotranspiration (Claessens et al. 2006). These changes on land indirectly impacted the estuary as suburbanization, sewerage, and dams altered water, nutrient, carbon and sediment loads. Salt marsh drainage patterns were modified in colonial times to facilitate the harvest of salt marsh hay and by extensive ditching for mosquito control in the 1920s and 1930s.

Human activity in the watersheds and estuary has also led to changes in many animal populations. Dams created barriers to migration and spawning leading to drastic declines in anadromous fish, and many other fish populations have fluctuated in response to human fishing pressure. Large freshwater impoundments were created out of salt marsh habitat to attract nesting waterfowl. Beaver were extirpated from the watersheds by 1750 and did not return until the 1920s. Their populations increased rapidly in the 1990s and now the influence of beaver dams on river hydrology rivals that of suburbanization and human dams.

Coupled with these local changes within the watershed and estuary are large-scale regional changes such as rising sea level and storminess (Hayden & Hayden 2003). All these changes are occurring worldwide to different degrees and it is our goal to transfer knowledge gained from the PIE LTER to other

coastal regions. To do this it is necessary to adopt a broad conceptual framework of linked land-margin ecosystems, and develop models and theories that are generally applicable to all coastal regions.

There has been an increased recognition of the need to incorporate landscape patterns and connections among landscape patches into ecology, from populations to food webs to ecosystem dynamics (Massol et al. 2011). Because of the rapid rate of change occurring in land-margin ecosystems, it is critical to understand how spatial patterns and connectivity influence ecosystem processes. Although applying a landscape (Turner et al. 1995; Reiners et al. 2001) or “meta-ecosystem” (Loreau et al. 2003) concept to understand and predict the impact of change has been extensively applied in terrestrial ecosystems, principles of spatial ecology have been less frequently applied in coastal and marine ecosystems. However, because of their highly connected nature, “seascape” ecology is emerging as a powerful approach to understand and manage coastal ecosystems (Pittman et al. 2011; Cicchetti and Greening 2011; Boström et al. 2011).

Understanding energy flow in coastal ecosystems requires a seascape perspective due to the large diversity of habitats, variability in both the quantity and quality of organic matter sources, and the importance of migrating animals. Migrating species that use estuaries seasonally dominate the total animal community in both species diversity and abundance and provide an important trophic subsidy (Deegan 1993; Deegan et al. 2000). Therefore, land-margin ecosystems allow for a robust test of the importance of resource subsidies in a diverse landscape (Polis et al. 1997, 2004; Marcarelli et al. 2011).

Rapid local changes that alter the land- and seascape mosaics as well as the connections between them are occurring against a backdrop of regional to global disturbances in the coastal zone such as climate change, sea-level rise, and over fishing. Theories of the interactions of landscape form and ecological function, such as are being developed for fluvial landscapes (Fisher et al. 2007; Poole 2002; Thorp et al. 2006), may be adapted to examine dynamic interactions between form and function in land-margin ecosystems for both biogeochemical processing and food web dynamics.

Finally, land-margin seascapes are characterized by the presence of strong temporal and spatial gradients in the availability of carbon and nutrients and by large redox gradients. As a result, critical ecosystem processes such as denitrification and the emission of trace gases occur in “hot spots and hot moments” that cannot be predicted by modeling average conditions (McClain et al. 2003). These gradients are not static in space or time. A fuller understanding of how element cycling is influenced by seascape patterns and the connections between patches will enhance our ability to model and predict how element cycling will be altered by changes in human activities, climate and sea level.

2.2 EVOLUTION OF OUR CONCEPTUAL FRAMEWORK

Our conceptual framework for the LTER has evolved over the past 14 years to reflect our improved understanding of how coastal ecosystems respond to changes in 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.*” Our original conceptual model (Fig. 2.1) focused on change over time, and held the implicit bias that climate, land-use change, and sea-level rise were *outside* forcing functions that altered key drivers (the fluxes of water, nutrients, and organic matter), eliciting an *internal* ecosystem response such as changes in material processing, primary and secondary production, and food web structure.

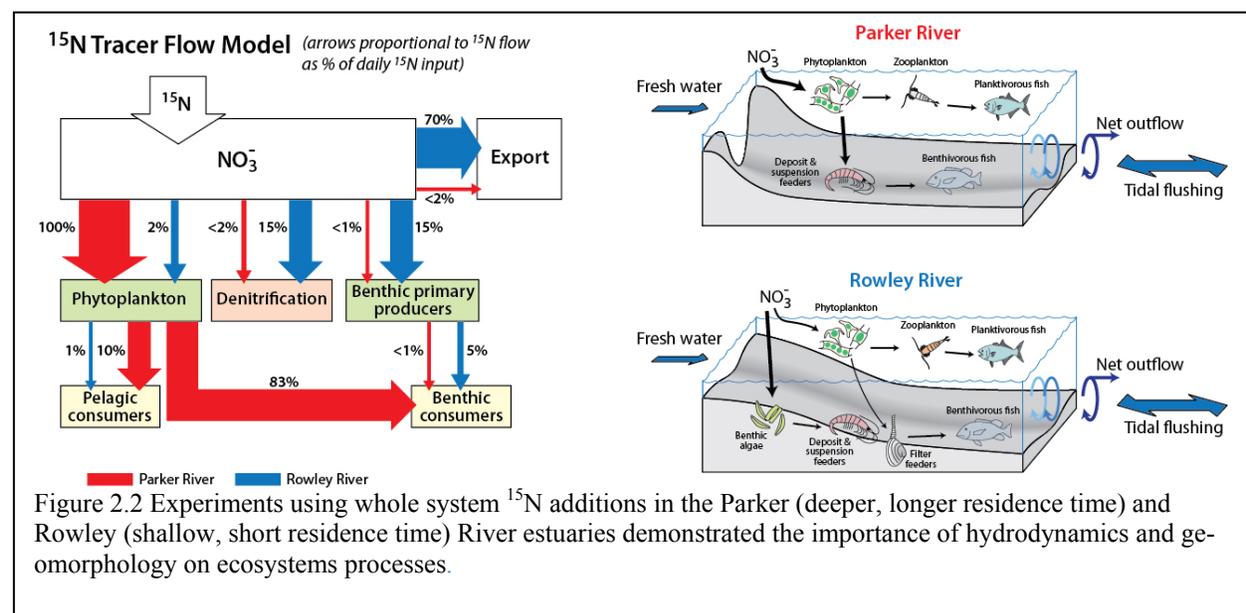
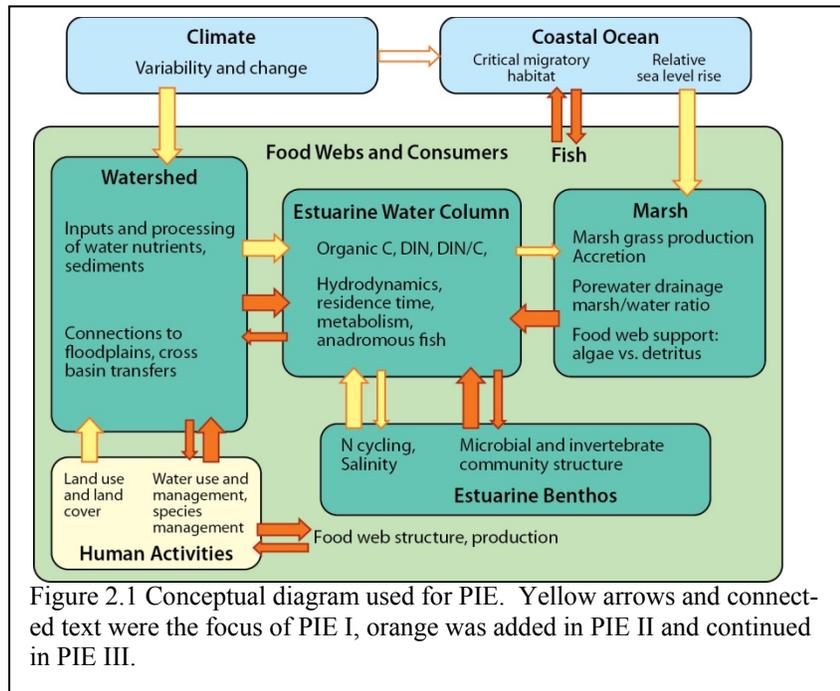
A primary hypothesis tested in PIE I was that the interaction of inorganic nutrients with the quality and quantity of organic carbon and organic nitrogen plays an important role in determining the trophic structure, production and efficiency of estuarine food webs (Fig. 2.1). We expected that when organic matter inputs to the estuary from the watershed were large relative to inorganic nutrients we would find a relatively inefficient microbial loop dominated by small phytoplankton and microzooplankton. When nutrient inputs were larger relative to organic matter inputs we expected to find a more efficient food web dominated by larger diatoms and macrozooplankton. Whole system experiments in the contrasting Parker and Rowley river estuaries (Holmes et al. 2000; Hughes et al. 2000, Tobias et al. 2003a,b), coupled with a large mesocosm experiment (Vallino 2000; Giblin & Vallino 2003), monitoring data, and intensive process studies in the estuary (Hopkinson et al. 1999), revealed that this hypothesis was not supported. In-

stead we found that *hydrology* played an enormous role in structuring the food web by altering the residence time of water and plankton (Vallino & Hopkins 1998). We found that pelagic phytoplankton dominate primary production in the high residence time Parker River Estuary, while benthic production dominates in the shorter residence time Rowley River estuary (Fig. 2.2). Differences in the primary production resource base (pelagic vs. benthic) cascades throughout the food web (Hughes et al. 2000).

During PIE I we made substantial progress understanding how rising rates of sea level impact marshes. Through experimental manipulation of nutrients and elevation, and long-term elevation monitoring, we found that PIE marshes responded similarly to marshes in South Carolina to changes in relative sea-level rise (RSLR), despite being fundamentally different in structure (dominant marsh plant, climate, tidal range, peat vs mineral sediments). This link between RSLR and marsh

productivity led to a generally applicable model of marsh response to sea-level rise (Morris et al. 2002).

Based upon our results in PIE I, we shifted our focus to examining the controlling influence of water flow and residence time on rates and locations of biogeochemical processes, food web structure and microbial community structure (Fig. 2.1). We quantified how hydrology controls N cycling both in the watershed (Wollheim et al. 2005, 2008a; Pellerin et al. 2008) and in the estuary through its impact on estuarine salinity and C and N inputs (Giblin et al. 2010; Weston et al. 2010). We found hydrology structures



both pelagic (Crump et al. 2004; Crump & Hobbie 2005) and sediment microbial communities (Mondrup 2000; Bernhard et al. 2005, 2007, 2010). Estuarine hydrodynamics affect water column metabolism through creek bank drainage, which is an important source of carbon supporting estuarine water column respiration (Raymond & Hopkinson 2003; Vallino et al. 2005; Gardner & Gaines 2008). We further developed our understanding of the role of marsh ecosystem processes in determining whether marshes could keep up with sea-level rise (Morris 2006). To examine this phenomena we co-organized a Chapman conference on "Salt marsh geomorphology: Physical and Ecological Effects on Landforms" (Torres et al. 2006). Interactions between nutrient delivery, marsh grass production, and food web responses were examined in a large-scale marsh creekshed experiment (TIDE; Deegan et al. 2007).

During PIE II it became evident that *geomorphic change* in our system was occurring at a rapid rate and this was incorporated into our conceptual model (Fig. 2.1). Human actions that alter stream flow directly (paving, water withdrawals, and sewerage), as well as indirectly (allowing beaver to return), were leading to major geomorphic changes in the river network. In the marsh, a comparison of 1950 and 2005 remote sensing imagery showed substantial changes in the abundance and distribution of vegetation, ponds and creeks throughout the salt marsh (Millett et al. 2010 and Q1B below). The causes of these marsh geomorphic changes are not well understood. The relative importance of sea-level rise (Morris et al. 2002; Mudd et al. 2009), sediment legacies (Kirwan et al. 2011), and nutrient inputs (Deegan et al. 2007) which are all being investigated within our program, are also under debate in the community as a whole (e.g. Turner et al. 2009 vs. Day et al. 2005). The responses of the marsh to changes in drivers are complex and occur on decadal time scales, yet understanding the mechanisms of response of coastal marsh ecosystems is critical to predicting and managing their fate worldwide.

In PIE III we have begun to directly address how geomorphic change shapes organic matter and nutrient transformations in linked watershed and coastal ecosystems. **Our overarching goal for the remainder of PIE III is to understand how external drivers, ecosystem dynamics, and human activities interact to shape ecological processes in a mosaic of coastal landscapes and estuarine seascapes.** This framework is designed to: (1) examine linkages and feedbacks between the watersheds, marshes, estuaries and coastal ocean in more detail; (2) identify the role of geomorphology and geomorphic change on ecosystem processes, and understand how ecosystem processes, in turn, alter geomorphology; and (3) incorporate the human dimension in a dynamic way that no longer treats humans as external drivers whose actions are unimpacted by within-system changes. This evolution in focus allows us to address fundamental questions concerning controls on matter and energy flow in linked coastal ecosystems and to begin a broader synthesis between our program areas. Explicit inclusion of humans brings the PIE-LTER into the framework set by the LTER Research Initiatives Subcommittee to NSF for "Integrating Science for Society and the Environment" (ISSE).

SECTION 4.0: RESPONSE TO 2007 SITE REVIEW and 2010 PANEL

The 2007 review team was extremely positive about PIE II. They had three primary recommendations for improvement. First was that while PIE was making progress synthesizing within specific research areas, we needed to increase integration across research areas and to synthesize results across other coastal sites. Second, they challenged us to incorporate ecological theory more directly and obviously in how we present our research themes and hypotheses. They suggested that the conceptual framework for PIE III should be updated to reflect the evolution in our program. Finally, they pointed out that much of the work on consumers was funded by leveraged projects and encouraged us to directly focus on some key prey and predator species, including birds as they are abundant in our system.

In the PIE III proposal we reorganized our programs to provide more integration across research areas. For example we made work on benthic metabolism integral to the carbon cycling work in the watershed, marsh and estuarine areas rather than a category unto itself. We expanded our conceptual framework to include the role of *geomorphic change* to better reflect the important changes occurring in coastal systems. We also expanded our collaborations with other coastal sites, both LTER and elsewhere, to better understand how sea-level rise impacts sediment accumulation and the carbon cycle of coastal systems. We added new work on birds, striped bass and herring into PIE as core areas. Our research on other con-

sumer species increased, although much was still carried out by leveraged funding. An ongoing project (NSF-TIDE, lead PI Deegan) was doing a considerable amount of research on top-down and bottom-up controls on intermediate consumers and Hopkinson launched a large effort on shellfish.

The 2010 panel had two major criticisms of the PIE III proposal and a number of additional comments. Below we address their review.

1) There was a lack of evidence that contemporary ecological theory was being integrated into our project, especially in food webs, and there was a lack of a strong integrative framework between the groups working within the estuary.

As described above, and in the questions below, we have more clearly grounded PIE questions in contemporary ecological theory. We will use the landscape/seascape framework to understand how linked coastal ecosystems respond to changes in climate, sea level, and human activities. Because land-margin ecosystems are very dynamic they represent challenging but important places in which to test and further develop conceptual and mathematical models of landscape ecology. In the remainder of PIE III we will focus our research questions around two themes: 1) *What controls the spatial arrangements and connectivity between ecological habitat patches (sensu Roundtree & Able 2007) in the coastal zone; and 2) How do the spatial arrangement and the connectivity between ecological habitat patches in coastal watersheds and the estuarine seascape influence ecological processes?* This new structure provides a framework that unites the research goals from each element of our land/seascape mosaic and facilitates the integration of results.

Although it has always been in our thinking (Deegan 1993) we have more explicitly linked our work on resource subsidies between different landscape and seascape elements into more general theories of resource subsidies in a heterogeneous landscape (Polis et al. 1997, 2004; Marcarelli et al. 2011). Our research has always been structured to gain a better understanding of how spatial and temporal changes create zones of intense biogeochemical cycling (i.e. McClain et al. 2003) but we will now explicitly examine how spatial arrangements and connectivity between patches creates these zones. Finally, we will begin to integrate newly emerging theories and models of biogeochemical processes into a spatial perspective (Vallino 2010, 2011).

2) There was a lack of information about the role of intermediate consumers in the function of the food web and we had put much of our focus on a few sentinel species such as mummichog and bass.

We unfortunately did not discuss our previous and current work on intermediate consumers and food webs in the prior PIE III proposal in adequate detail. However, we have not neglected this in our research. During PIE II, 44 of our papers were related to food web research, and food webs were also a major focus of PIE I. Through this previous work we have an excellent grasp on the food webs and species in our system (e.g., Deegan & Garritt 1997; Holmes et al. 2000; Hughes et al. 2000; Galván et al. 2008; Johnson 2011). We have a great deal of evidence on how intermediate consumers respond to changes in bottom-up drivers through our detritus removal experiment (Buchsbaum et al. 2009) and through the TIDE whole creek nutrient enrichment experiment (Deegan et al. 2007; Fleeger et al. 2008; Johnson et al. 2009, Pierre et al. in review). This work is covered in more detail in Questions 2C and D. There were some gaps in our data, especially in pelagic consumers, which we are addressing by analyzing zooplankton samples that we had archived but not analyzed. Last year we reallocated funds to Dr. Turner (U. Massachusetts, Dartmouth) and his Ph.D. student to analyze our time-series of zooplankton samples. Dr. Turner has extensive experience with zooplankton from this region so we will be able to put PIE findings into a broader context. As planned, in PIE III we added a post-doctoral investigator to work on intermediate and higher consumers. Finally, over the last several years we have redesigned and implemented a regular sampling of consumers as part of our core long-term data.

Expansion of the PIE team to include a theoretical food web ecologist was a recommendation of the 2010 panel but not the 2007 review team. The PIE team has considered this recommendation very carefully but based upon our programmatic emphasis we feel it is not a top priority. We believe our team is strong in food web ecology and addresses theoretical issues on food web dynamics (Q2 C,D,E). We are also initiating synthesis activities with other coastal wetland LTER sites examining controls on food web structure which we believe will be an effective way to move our science forward.

Additional comments: Several of the criticisms of PIE III appear to reflect deficiencies in the description of our past work in our previous proposal that we believe are not issues with the strength of our research program. a) The panel felt we were not considering the fact that our watersheds contain human infrastructure that modifies the hydrology. In fact, we have quantified changes in water withdrawals through time and its impact on runoff at the watershed scale (Claessens et al 2006), examined impacts of impervious surfaces on hydrological flow paths (Pellerin et al. 2008), quantified the impact of sewer systems on basin scale N budgets (Filoso et al. 2004; Williams et al. 2004), examined the impact of impervious surfaces on N retention (Wollheim et al. 2005), and examined how people manage their residential land, including a focus on water use and water-use restrictions (Hill & Polsky 2005, 2007; Polsky et al. 2009; Chowdhury et al. 2011; Harris et al. 2012; in review). This is also a very active area of proposed research in the remainder of PIE III (PIE IIIB; Q1A). b) The panel suggested our marsh work was “30 years out of date”. This reflects the belief of the panel that we were ignoring recent work on consumer controls on marsh production. We have examined this but have found that marsh grass grazers do not play a key role in our system (See Section 1; Johnson & Jessen 2008). While consumers clearly play a role in some systems at some times (Pennings & Silliman 2005), our work shows that physical factors, such as relative sea-level rise, and biogeochemistry are primary drivers of marsh production at PIE and elsewhere and must be considered.

2.3 CONCEPTUAL FRAMEWORK for PIE IIIB

In PIE IIIB we will continue to take an integrated system-level approach that will allow us to develop a *predictive* understanding of how coastal ecosystems will respond to changes in human activities, sea level and climate. Over the next four years we will build upon the progress we have made in understanding the importance of spatial patterns and connections across the land-margin ecosystem. **Our overarching goal is 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 control ecosystem processes, is both a fundamental science question and a critical management question for coastal policy makers. During PIE IIIB we will continue to address the role of temporal change and variability in climate, sea-level rise and human activities on ecological processes in our long-term monitoring (Fig. 2.1) but we will also initiate new activities that examine spatial arrangements and connectivity (Fig 2.3).

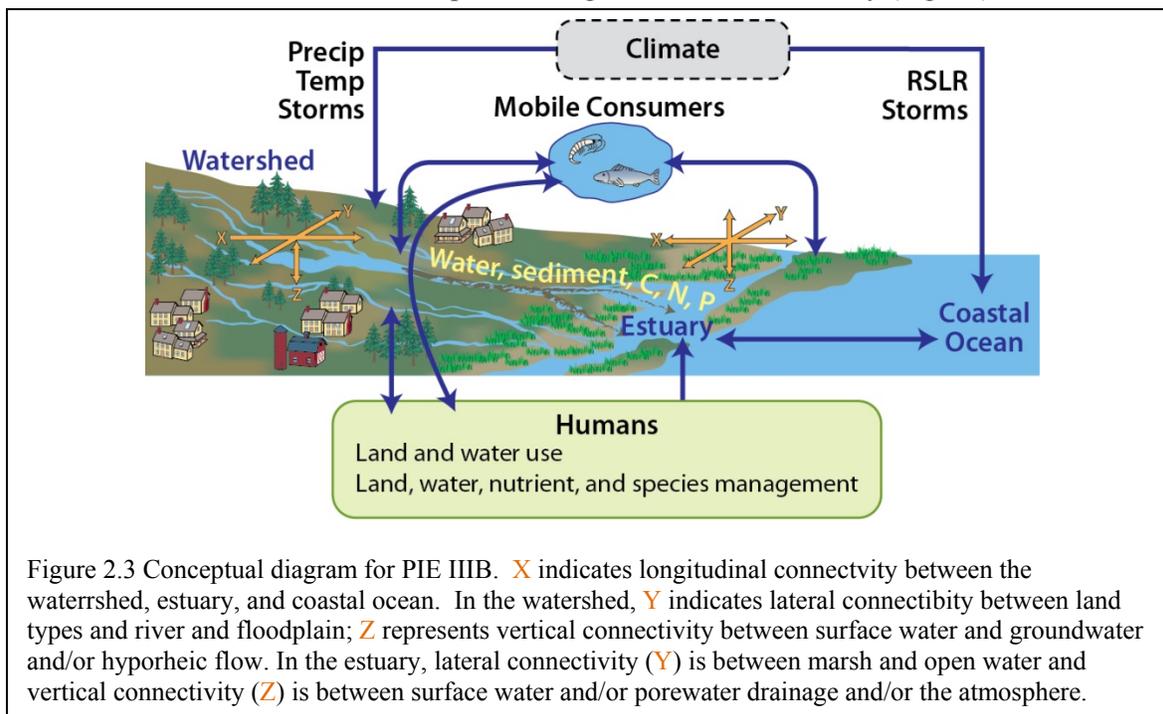


Figure 2.3 Conceptual diagram for PIE IIIB. X indicates longitudinal connectivity between the watershed, estuary, and coastal ocean. In the watershed, Y indicates lateral connectivity between land types and river and floodplain; Z represents vertical connectivity between surface water and groundwater and/or hyporheic flow. In the estuary, lateral connectivity (Y) is between marsh and open water and vertical connectivity (Z) is between surface water and/or porewater drainage and/or the atmosphere.

To address this we will: 1) quantify historical changes in spatial arrangements and connectivity and relate these to changes in drivers, 2) supplement our long-term core monitoring with additional measurements in areas with different spatial arrangements and connectivity, 3) continue existing and conduct new large scale manipulative and modeling experiments, and 4) continue to develop models that can be applied in a complex spatial environment.

Connectivity between ecological patches is context and scale dependent. For example, physical structures in the river network may decrease the connectivity between the ocean and the spawning grounds for anadromous fish while these same structures increase the lateral connectivity of river water with riparian flood plains and increase biogeochemical cycling. Connectivity to areas of high prey densities may involve spatial scales of kilometers for striped bass but only meters for small invertebrates. We use connectivity in the broadest sense to include both structural and functional connectivity.

2.4 SPECIFIC QUESTIONS AND DETAILED APPROACHS

Theme 1) What controls the spatial arrangements and connectivity between ecological habitat patches in the coastal zone?

Q1A. How do human land use, infrastructure placement, and species management impact the connectivity of terrestrial areas to the river network and different aquatic patches within the network?

Hypotheses: 1) *Residential development and infrastructure placement near streams increases the connectivity of urban land to the river network through rapid redistribution of water and materials, leading to greater impacts on headwater stream hydrographs and nutrient transfer from land to water.* 2) *Inadequate road culverts and changes in beaver management in these shallow sloped watersheds have slowed drainage and increased ponding, resulting in increased heterogeneity in the river system, increased residence times, and reduced upstream-downstream connectivity. These changes partially offset the flashier runoff associated with increased impervious surfaces in suburban areas.*

Rationale: The extent of urban and suburban land cover in watersheds has been widely linked with higher concentrations of nutrients in streams and rivers (Williams et al. 2004; Walsh et al. 2005; Kaushal et al. 2008; Bernhardt et al. 2008). Because the position of sources relative to hydrologic flowpaths creates source or removal “hotspots” (McClain et al. 2003), it is increasingly important to understand not only the total nutrient and sediment sources in watersheds, but their spatial arrangement (Gergel et al. 2005), and their interactions with hydrologic conditions (Band et al. 2001; Bracken & Croke 2007). In urban watersheds, the infrastructure built to move and treat water shapes connectivity by transferring water and nutrients across basin boundaries (Groffman et al. 2004; Lookingbill et al. 2009). Increased understanding of the role of spatial connections in urbanizing areas is needed because encroachment of suburban development into native ecosystems and water supply areas is accelerating (Wickham et al. 2011) and because the arrangement of patches that have disproportionately large influences (e.g., riparian buffers) can guide watershed management (Weller et al. 2011). Our watershed measurements indicate that while nitrate concentrations in streams are highly correlated with the intensity of urbanization, considerable unexplained variability remains (Williams et al. 2005; Wollheim et al. 2005).

Material flows and trophic responses throughout river systems are strongly influenced by a wide variety of geomorphologically distinct aquatic subsystems that are differentially connected in space and time (Poole 2002; Fisher et al. 1998; Thorp et al. 2006). While the River Continuum Concept remains an important underpinning of aquatic ecosystem theory (Vannote et al. 1980), serial discontinuities (sensu Poole 2002) caused by natural features (e.g. lakes, floodplains, wetlands, beaver ponds), and human-built infrastructure (Tockner 2000; Benda et al. 2004; Wollheim et al. 2008a; Kling et al. 2000; Burchsted et al. 2010) substantially alter dynamics. These features modify residence times, biotic activity, and connectivity in longitudinal (upstream-downstream), vertical (channel-groundwater), and lateral (channel-floodplain) directions (Ward et al. 1989). Beaver ponds have expanded considerably in our study basins, accelerated by changes in trapping laws in the late 1990’s (Fig. 2.4; Smith & Mather 2011; submitted). Spatial arrangement of these discontinuities can have great influence on whole system responses (Poole 2002; Gergel et al. 2005), particularly in urbanized areas where material sources are distributed heteroge-

neously across the landscape. Connectivity is driven by hydrologic forcings, which are changing directly and indirectly due to altered flow regimes associated with urbanization and changing climate. A greater predictive understanding of riverine landscape dynamics will require moving beyond a channel perspective to account for the role of fluvial discontinuities within river networks (Poole 2002; Wollheim et al. 2008a,b; Helton et al. 2011). This requires characterization of the major classes of heterogeneity and their integration into riverine models.

Approach: We have regularly monitored discharge, dissolved and particulate C, N, and P, and total suspended sediments for 10 years in three headwater catchments in the Ipswich and Parker River watersheds that represent end-member land covers (urban, forest, wetland). To test hypothesis (1), we will expand regular monitoring of stream discharge and stream water chemistry to four additional headwater catchments with variable arrangement of infrastructure. We will use our newly-developed basin-wide map of suburban land covers (from 50 cm imagery; Fig. 2.4) linked with recently collected LIDAR elevation data and existing maps of inter-basin water and sewage transfer (Claessens et al. 2006) to quantify the spatial connectivity of residential areas to stream channels (e.g., King et al. 2005; Ganio et al. 2005) in all our monitored catchments, including 40 additional headwater catchments that are periodically monitored

(Williams et al. 2004; Wollheim et al. 2005). The four new headwater sites will have similar overall land cover and population, but variable arrangement and management, including: (1) residential area predominantly nearer stream channels but with low intensity of water infrastructure (e.g. septic systems, no storm drains); (2) residential area farther from stream channels with low infrastructure; (3) residential areas nearer the stream channels with large amounts of water infrastructure (sewers, storm drains) and; (4) residential areas farther from stream channels with large amounts of infrastructure. We will apportion solute and total suspended solid concentrations to storm- and baseflow fluxes. These new sites will be compared

with our longer term monitoring in the three end member headwater sites. Sampling over multiple years will allow comparison of impacts across annual climate variations that are projected for New England to include greater precipitation extremes (Hayhoe et al. 2006). We will test the robustness of these patterns across our broader array of 40 headwater watersheds (Williams et al. 2004; Wollheim et al. 2005) in which spatial connectivity of residential areas to stream channels will be characterized in conjunction with solute chemistry.

The spatial distribution of human activities (e.g., lawn irrigation, sewage disposal, water withdrawals) greatly influences water and material budgets and terrestrial-aquatic connectivity in our system (Claessens et al. 2006). Feedbacks on social activity are an additional influence. For example, summer droughts are stressors that dictate whether towns implement watering bans and/or switch to other water sources (Hill & Polsky 2007). These decisions influence the quantity and allocation of flows of water and associated nutrients. We will use our spatially-explicit database of residential household water consumption, water pricing, summer lawn irrigation, community demographics, socio-economic characteristics, and water-use restrictions to generalize understanding of the spatial variation of lawn irrigation and water bans (Runfola et al. in review) for all 25 towns in the watersheds. This database will be integrated with our 50-cm land-

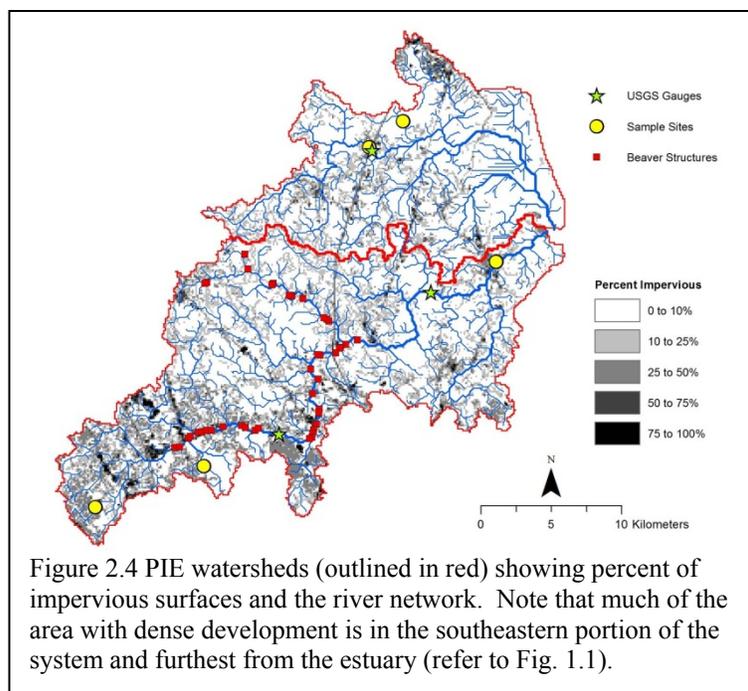
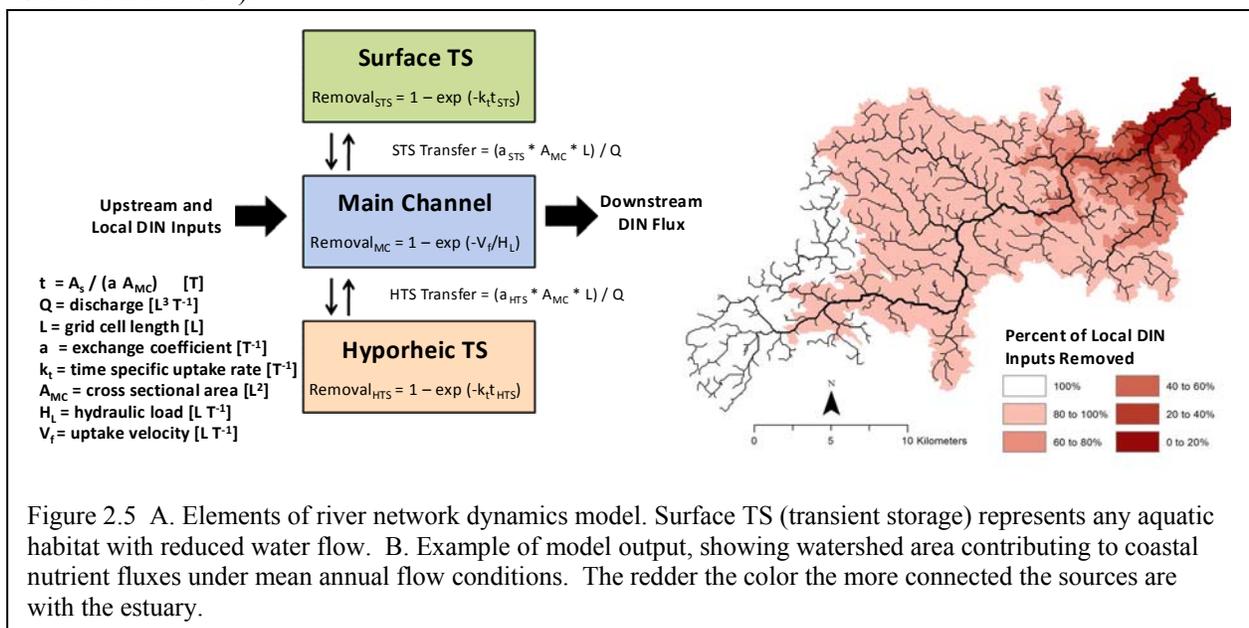


Figure 2.4 PIE watersheds (outlined in red) showing percent of impervious surfaces and the river network. Note that much of the area with dense development is in the southeastern portion of the system and furthest from the estuary (refer to Fig. 1.1).

cover classification for the PIE domain (Polsky et. al. 2012; e.g., Fig. 2.4) permitting multivariate geospatial analyses of household water use and town water-use restrictions (c.f. Hill and Polsky 2007; Runfola et al. in review; Krahe 2012). We will test whether the locations of specific land-covers correlate with locations of high, medium or low water-use. The effectiveness of socio-ecological feedbacks on biophysical responses will be assessed using the field measurements (above).

To test hypothesis 2, we will develop spatial data sets of river network habitat structure (e.g. dam ponds, beaver ponds, road crossings, floodplains) through a combination of newly collected LIDAR data, existing aerial photography, GIS, and field visits (Walter & Merritts 2008; Millette et al. 2010; Carbonneau et al. In Press). The LIDAR data for our entire watershed supported in part through LTER supplemental funds, will soon be available from flights conducted in May 2011 (Dan Walters, USGS, pers comm.). Field surveys will be used to validate these data sets. We will use our 50-cm resolution land cover map, enhanced with LIDAR and other modern object-based technologies, to identify aquatic features for the contemporary period, e.g. ponding caused by beaver dams, road culverts, legacy and natural geomorphic features and riparian cover and height. We will construct a similar map circa 1990 from aerial photography to quantify changes in the distribution of aquatic habitats between 1990 and 2005 (Pontius & Li 2010; Pontius & Lippitt 2006). We will also produce a validated, fine-resolution map for 2012, to estimate spatial and temporal trends in various land use and land cover features. We will identify spectral signatures of key landscape characteristics needed for map construction and validation. Ultimately, we will use these maps to partition overall landscape change into two components: quantity and location (Pontius & Millones 2011). All spatial data sets will be georeferenced to our digital river network (Fig. 2.5). We will then use these maps to quantify the temporal changes in the distribution of ponded areas within the river network relative to stream order and urban regions. Field surveys on a subset of sites will be used to develop mean depth and velocity vs. size relationships, which we will then use in our river network model to quantify residence times at various spatial scales (catchment to river network) (e.g., Stewart et al. 2011).



Q1B How will tidal marsh area, configuration, and elevation (relative to mean sea level) change with rising sea level and changes in sediment delivery?

Hypotheses: 1) Tidal marshes maintain elevation relative to local mean sea level by accreting mineral sediment, organic matter, and transgressing inland. 2) As sea-level rise accelerates there will be: a) an increase in marsh inundation time, b) a decrease in hydraulic gradient between the marsh surface and mean sea level (MSL), c) an initial increase followed by a decrease in unit area in plant productivity, d)

an initial increase in marsh ponding, and e) changes in material exchanges. As a consequence, the relative elevation and area of existing tidal marshes will decline and there will be a replacement of high marsh dominated by *Spartina patens* with low marsh dominated by *S. alterniflora*.

Rationale: Sediment and nutrient supply to the estuary and marshes is regulated by land use, natural and anthropogenic changes in hydrology and river network geomorphology, and climate. Climate change will alter the hydrological cycle, as well as temperature, growing season length, and biogeochemistry. Altered nutrient or sediment supply affects marsh above ground primary production, accretion of mineral sediment, and relative marsh elevation. Changes in the hydraulic properties, area of intertidal habitat, and length of edge have implications for food webs, and energy and material flows. The ability of the marsh to respond to relative sea-level rise (RSLR) is highly dependent on interactions among these various factors which will determine the elevation, vegetative composition and extent of the marsh platform.

At PIE we have observed considerable erosion at the edge of the marsh platform (Fig. 2.6a). Some of this eroded material is redeposited onto tidal flats which become colonized by *S. alterniflora*, creating new marsh significantly below the existing marsh platform (Fig. 2.6b), while some eroded material is redeposited on the high marsh platform. This process of cannibalization is probably important for maintaining the elevation of the remaining platform, as suggested by the ^{14}C ages of the organic ‘fines’ which are uniformly old, 1,800 ybp, in the top 25 cm of sediment (Wang 2008). Ice rafting of sediment onto the high marsh platform appears to be important for the redistribution of mineral sediment as well as eroded organic matter (Fig. 2.6c, Argow et al. 2011). Ice rafting also is one of the mechanisms that initiates pond formation (Fig. 2.6d, Redfield 1972). Ponds enlarge over time through enhanced decomposition of peat, and as ice rips away the margins. The importance of ice rafting at PIE may decline as global warming raises winter temperatures. However, ponds form even in the absence of ice. These ponds can expand and deepen until they connect to a creek. Once they drain, the lower elevation pond bottoms are colonized by *S. alterniflora* and begin to accrete sediment.

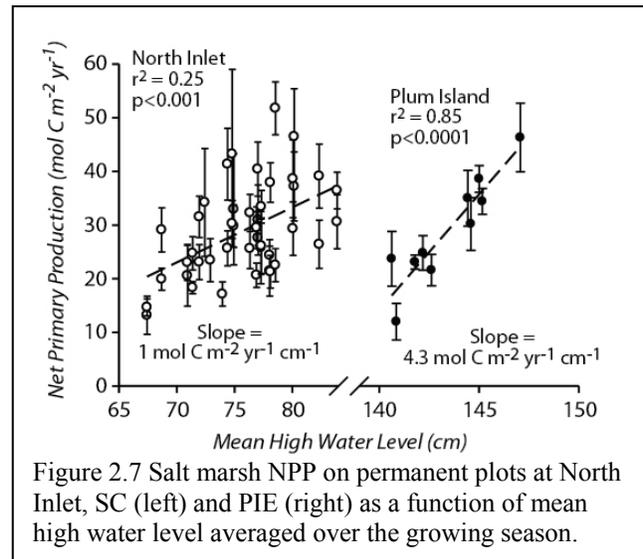


Figure 2.7 Salt marsh NPP on permanent plots at North Inlet, SC (left) and PIE (right) as a function of mean high water level averaged over the growing season.

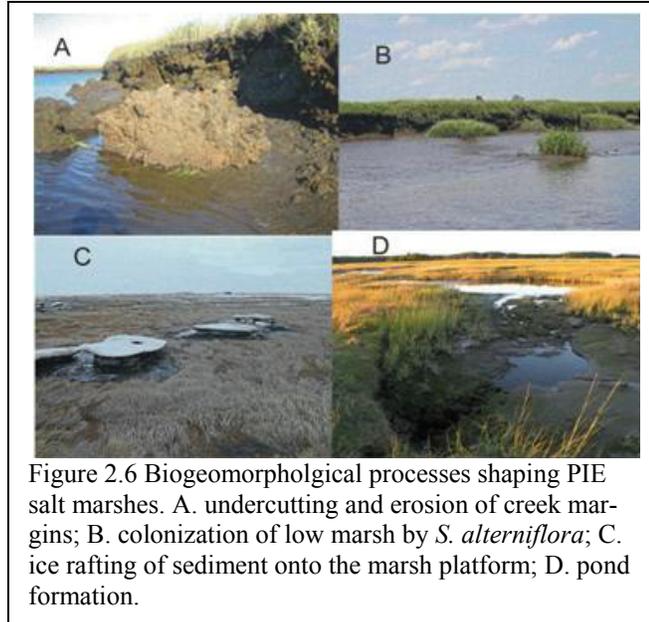
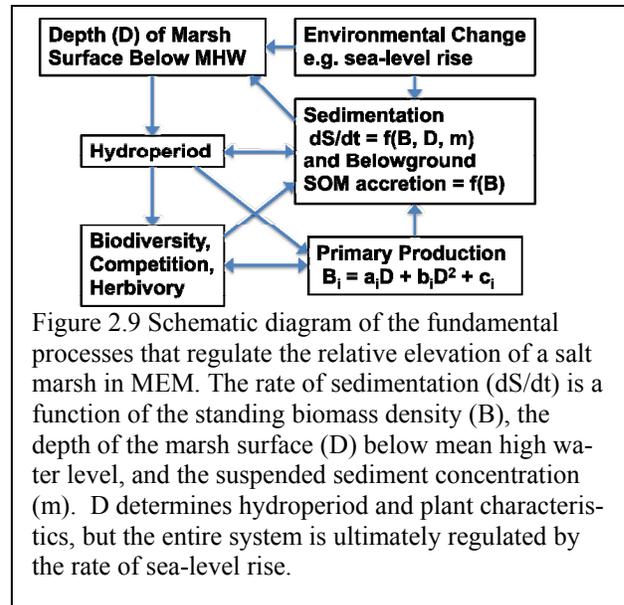
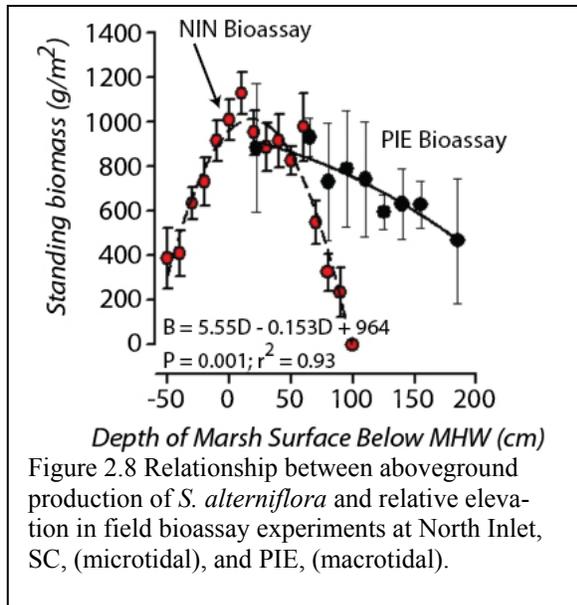


Figure 2.6 Biogeomorphological processes shaping PIE salt marshes. A. undercutting and erosion of creek margins; B. colonization of low marsh by *S. alterniflora*; C. ice rafting of sediment onto the marsh platform; D. pond formation.

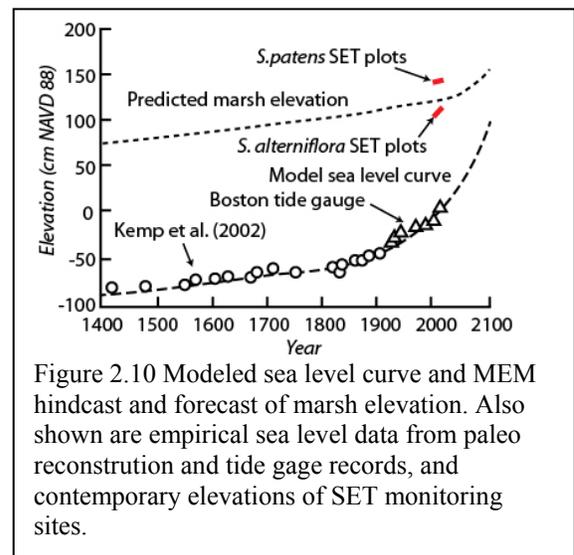
Organic matter production by the marsh also helps maintain elevation of the marsh platform. Annual salt marsh primary production varies with anomalies in mean sea level (Morris 2007a; Morris & Haskin 1990, Fig. 2.7.) This variation is statistically and ecologically significant, however, bioassay experiments have shown that the effect can be positive or negative, and sensitivity varies, depending on the relative elevation of the marsh surface (Fig. 2.8). These experiments document that marsh species have a range of flooding tolerance and an optimum (Shelford 1931), which is a function of relative elevation and tide range. Discovery of the temporal patterns in NPP was possible because we employ



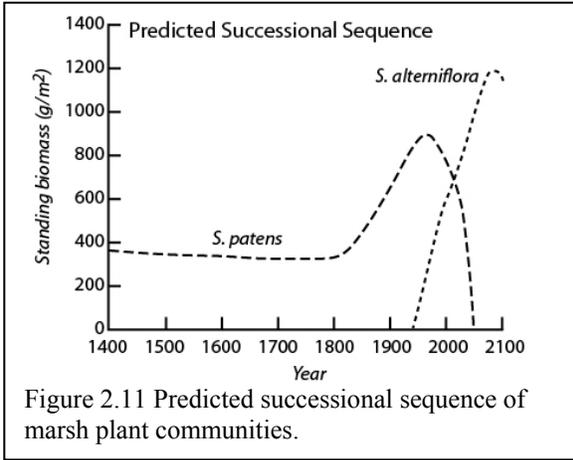
non-destructive monitoring on permanent plots (Morris 2007a) which are not corrupted by spatial variability.

Our proposed research is guided by a theoretical model, the Marsh Equilibrium Model (MEM) that uses feedbacks among the plant community, sediments and tides to predict how the relative elevation of a salt marsh is affected by rising sea level (Morris et al. 2002, Fig. 2.9). The model assumes that the sedimentation of minerals carried by tides over the marsh surface increases with the concentration of suspended solids, duration of flooding (Friedrichs & Perry 2001), and standing biomass density (Morris et al. 2002). In addition to surface deposition, production of organic matter contributes to the total accumulation rate (Reed 1995; Turner et al. 2001). From this model (Morris et al. 2002) we hypothesize that the depth of the marsh surface below mean high water (MHW) and the rate of relative sea-level rise (RSLR) are proportional when the marsh surface and mean sea level are in equilibrium. Thus, as the rate of RSLR increases, the elevation of the marsh surface relative to MSL must decrease. PIE marshes are currently following this model. Furthermore, when the relative marsh elevation is greater than optimal (Fig. 2.10), rising sea level will increase the biomass density, which increases sedimentation (Fig. 2.9) and raises the elevation of the marsh (stabilizing feedback). If the elevation is sub-optimal, rising sea-level will depress biomass density and, consequently, sedimentation, and relative elevation will fall (destabilizing feedback). The transition is a tipping point, and it is determined by the rate of sea-level rise, the growth range of the vegetation, suspended sediment concentration, and tide range. This can be simulated using MEM (<http://jellyfish.geol.sc.edu/model/marsh/mem.asp>) for any marsh system.

MEM was used to hindcast and forecast the elevations and dominant vegetation of marshes at PIE. Hindcasts matched our understanding of the evolution of modern PIE marshes under a long-term (millennia) sea-level rise of about 1 mm/yr. The current marsh platform is dominated by *S. patens* and is about 25-30% organic matter, having equilibrated at the top of the tidal frame (Fig. 2.10), where mineral deposition becomes limited. Starting about 1800, RSLR began to



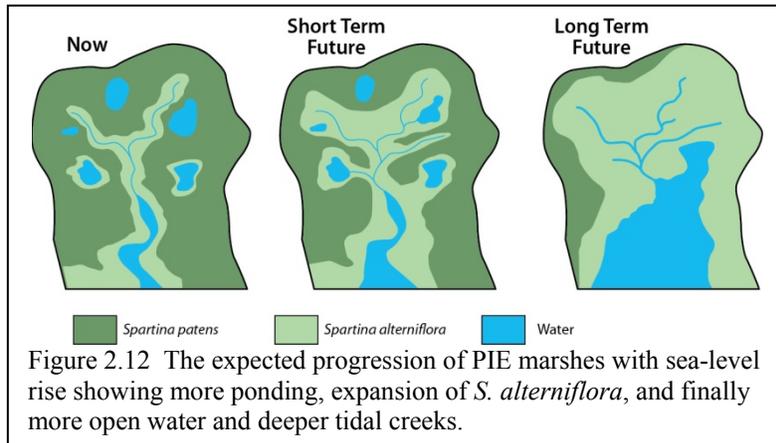
accelerate, causing a decline in marsh elevation relative to MSL. MEM predicts a continued decline in relative marsh elevation as RSLR continues to accelerate into the 21st century, and a transition from *S. patens* to *S. alterniflora* as the dominant vegetation (Fig. 2.11). Our observations (Fig. 2.6) show that existing high marsh is in fact transitioning to low marsh as a consequence of pond formation, creek bank erosion, and subsequent colonization by *S. alterniflora* of new, low marsh habitat.



Erosion of the margins is related to the increase in volume of the tidal prism (Hughes et al. 2009). MEM predicts the prism will increase because mean sea level is rising faster than the basin elevations, and the increase in volume and velocity of water will enlarge the channels. Theories of landscape allometry and hydraulic geometry support this prediction, having been applied successfully numerous times to describe simple scaling relationships among prism volume, landscape metrics and the hydraulic properties of estuaries. In addition, there is ample empirical evidence that the cross-sectional area and length of creeks increases with tidal amplitude (or tidal prism) (Allen 2000; Williams et al. 2002; Hood 2002;

Novakowski et al. 2004; Hughes 2009; Hood 2011). We predict the net result of all of these changes is a marsh with far less *S. patens* and wider tidal creeks and more open bay (Fig. 2.12).

Since above ground biomass of marsh grasses and sediment trapping are increased by nutrient additions, our model also predicts that marshes will accrete faster with increased nutrient delivery. However, others have suggested that increased N inputs decrease the marsh's ability to withstand sea-level rise due to a loss of peat and below ground biomass (Darby & Turner 2008; Turner et al 2009). The effect of N on below ground biomass appears to be quite variable with some sites showing an increase or no change with fertilization (Valiela et al. 1976; Anisfeld & Hill 2012; Morris per. obs. at SC) and others suggesting a decrease (Wigand et al 2009; Darby & Turner 2008). In our whole-creek, nitrate-addition experiments there has been significant creek bank failure in the long-term fertilized creeks and preliminary data suggests below ground biomass may have decreased (Warren unpublished data). Recently a second creek has been fertilized to see if patterns are repeated. The question of how nutrients influence marsh geomorphology is unresolved and is an important research focus at PIE.



Approach: To address the question of how marsh spatial arrangement and connectivity will change we will combine long-term monitoring of primary production, marsh elevations, tides, climate, and porewater chemistry with periodic remote and ground data collections, experimentation in the field and laboratory, and modeling. Long-term marsh monitoring: Long-term monitoring sites are located in the 2 major marsh types where we census plant populations, monitor pore water chemistry, and track marsh elevations. A monthly census of plant populations (Morris & Haskin 1990; Morris 2007a) provides unparalleled temporal resolution of salt marsh production. Porewater diffusion samplers are used to monitor depth profiles (0-100 cm) and temporal changes in porewater nutrient concentrations. Relative change in marsh surface elevation is measured seasonally to 1 mm accuracy using sediment erosion tables (SETs)

(Boumans and Day 1993; Cahoon et al. 2000). Small experimental plots at each site also receive monthly factorial N and P additions to determine nutrient interactions, and the whole-creek nutrient additions are continuing at least through another year. In addition, we maintain multiple SETs at PIE, including 6 in ponds in various stages of development to quantify marsh accretion rates.

New Activities: This year we began measurements of whole-marsh metabolism using the eddy covariance method. The turbulent exchange of CO₂ and energy fluxes between marsh and atmosphere is measured with a fast response IR gas analyzer and an ultrasonic anemometer (similar to Kathilankal et al. 2008 although we use a closed path system). The resulting CO₂ fluxes are nearly equivalent to the net ecosystem exchange (NEE) (gross primary production + respiration). We will complete the C budget required to calculate ecosystem NEE by measuring horizontal fluxes of dissolved inorganic carbon associated with tidal flooding within the tower footprint (see Q2B). The tower is within the Nelson Island marsh, an area that is changing rapidly, developing ponds and transitioning into a lower elevation marsh. During PIE IIIB we will continue these measurements and this summer we are installing a second tower in the West Creek area where *S. patens* and the high marsh platform has been stable with minimal ponding. These tower and creek measurements allow us to quantify the whole system carbon exchange in response to variations in sea-level, adding significantly to what we learn from above-ground production alone.

Remote sensing and GIS technologies will be used to characterize current marsh geomorphology, tidal creek drainage network configuration, pond development, and plant community distributions. Ground transects and analyses of aerial imagery and LIDAR data (Morris et al. 2005b; Millett et al. 2010) will be used to measure changes in plant community and marsh distributions. Additional permanent ground transects will be established across the marsh and extending to the uplands in order to ground-truth classifications of aerial imagery and to monitor migration of plant communities, building upon existing vegetation surveys begun in 1996 (Buchsbaum et al. 2006; Buchsbaum et al. 2009). Other ground surveys are being done in collaboration with the Massachusetts Audubon Society and the Governor's Academy throughout the various ecosystems in the Plum Island Sound area. Marsh productivity will be measured in permanent plots in the tower footprints. Measurements from these plots will be extrapolated to large areas by calibrating the biomass data from permanent plots against ground based NDVI measurements made with a UniSpec-DC spectral analysis system. Integrated rates of marsh productivity will be contrasted with measurements of aquatic system metabolism as described below.

During PIE IIIB we will continue field bioassay experiments designed to measure growth responses of vegetation to relative marsh elevation (Morris 2007a). We will examine the "decomposition potential" of peat using a flow-through modification of the thin disc system (Kristensen and Holmer 2001). We will compare decomposition "potentials" of peat exposed to nitrate and compare it to peat exposed to sulfate or oxygen alone. Outside funding supports measurements of belowground biomass at the fertilized sites.

Theme 2) How do the spatial arrangements and connectivity between ecological habitat patches in coastal watersheds and estuarine seascapes influence ecological processes?

Q2A. Have changes in the spatial arrangements and connectivity of aquatic patches in the watershed led to reduced longitudinal and increased lateral connectivity? Has altered connectivity resulted in changes in material flows, consumer biodiversity, and mobility of fish?

Hypotheses: 1) Altered abundance and connectivity of aquatic patches has led to a greater capacity of the river network as a whole to attenuate the flux of nitrogen, carbon, and sediments. 2) The arrangement of aquatic habitat patches relative to major nutrient source areas is a major determinant of the efficiency of material removal within the network. 3) Changes in spatial configuration of habitat patches that result from discontinuities such as beaver and human dams alter consumer food webs that further impact ecosystem function.

Rationale: Changes in aquatic patch distribution and connectivity have strong biogeochemical and trophic implications that are currently inadequately considered in many network scale analyses (Pringle 2001; Groffman et al. 2009). PIE watersheds are ideal model systems within which to address the role of spatial heterogeneity and changing connectivity within aquatic ecosystems. The recent expansion of ponded areas within the river system (see Q1A) likely contributes to elevated denitrification capacity through associated changes in biogeochemical reaction rates and residence times, reduced upstream-downstream connectivity, and increased lateral connectivity with riparian wetlands (Ward 1989; Poole 2002); Fig. 2.5c). These changes potentially contribute to the high N retention rates of PIE watersheds compared to other watersheds across the northeast (Howarth et al. 1996; Boyer et al. 2002) and the relatively stable export we have observed despite increased suburbanization, population, storminess and N inputs (Fig. 2.13a; 2.14). Since early 2000, an increasing proportion of DIN has been exported as NH_4^+ , consistent with more reduced redox conditions associated with beaver impoundments (Fig. 2.13b). Changes in impervious surfaces (Pellerin et al. 2008), lawn distribution and irrigation, and water management (Zarriello & Ries 2000;

Claessens et al. 2006) have led to additional changes in the flow regime that alter connectivity with abundant riparian floodplains. Future changes will occur with the planned removal of long existing human-made dams. River network biogeochemical models we have developed for the PIE basins have integrated findings across a wide range of field studies focused on *channels* of different size, including quantification of vertical connectivity, residence times, and reactivity (Mulholland et al. 2008; Briggs et al. 2009; Thouin et al. 2009; Briggs et al. 2010). These models have not accounted for the role of these discontinuities, and as a result have not adequately predicted biogeochemical activity of the entire river system (Wollheim et al. 2008a; Stewart et al. 2011; Helton et al. 2011). Discontinuities also affect aquatic communities, fish distributions, and connectivity of fish populations through such mechanisms as altered habitat, impaired movement, and reduced access to spawning and feeding habitat (Bednarek 2001; Cumming 2004; Calles & Greenberg 2009; Fullerton et al. 2010; Nislow et al. 2011; Wang et al. 2011;).

Approach: We will use a combination of monitoring, surveys, process measurements, experiments, and modeling to address these hypotheses. Long-term monitoring of discharge, dissolved and particulate C, N, and P, and total suspended sediment will continue at the three headwater sites (urban, forest, wetland) and at the two basin mouths (Ipswich R., Parker R.), in order to track

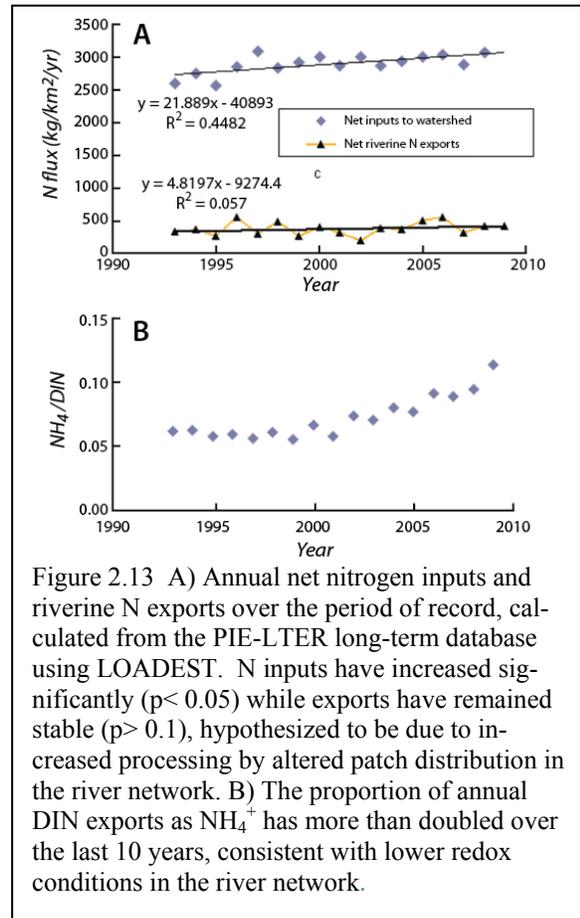


Figure 2.13 A) Annual net nitrogen inputs and riverine N exports over the period of record, calculated from the PIE-LTER long-term database using LOADEST. N inputs have increased significantly ($p < 0.05$) while exports have remained stable ($p > 0.1$), hypothesized to be due to increased processing by altered patch distribution in the river network. B) The proportion of annual DIN exports as NH_4^+ has more than doubled over the last 10 years, consistent with lower redox conditions in the river network.

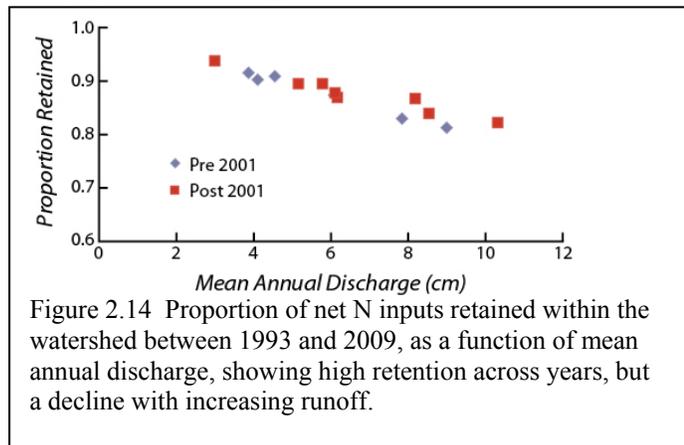


Figure 2.14 Proportion of net N inputs retained within the watershed between 1993 and 2009, as a function of mean annual discharge, showing high retention across years, but a decline with increasing runoff.

changing material inputs to the river network and exports from the watersheds, respectively. The additional sites proposed in Q1 will allow us to better assess the impact of alternative land-use and management configurations. We will continue annual spring monitoring of returning river herring at the downstream dams, conducted in cooperation with local watershed associations, to maintain a long-term database of anadromous fish returns. These data are essential for understanding the response of the whole system to the changing river network.

Field measurements: We will use our existing river network hydrological and biogeochemical modeling framework (Wollheim et al. 2008a; Stewart et al. 2011; Fig. 2.5a,b) as a foundation for testing the importance of serial discontinuities and patch arrangement and connectivity within the network across flow conditions. Our field activities will focus on improving this model. In addition to the spatial data sets and improved loading algorithms that account for the distribution of terrestrial sources described in Q1A, we require 1) estimates of hydrologic and organismal connectivity between patches, and 2) estimates of residence times and biogeochemical reactivity within patches, and their habitat quality. Upstream-downstream hydrological connectivity of various habitats is defined by the river network topology, and based on the position of heterogeneity along flowpaths (see Q1A). Lateral connectivity, which is time varying and flow dependent, will be estimated using stream gage height and geomorphic characteristics at sites with differing flow regimes and stream size. Measurements of organismal connectivity are described below. Measurements of connectivity, residence time, reactivity, and fish habitat quality in aquatic patches will take place in conjunction with several whole system manipulation experiments to test the effects of changing patch type on biogeochemical fluxes and fish populations.

Whole system manipulations and process measurements: We plan to conduct three riverine manipulation experiments with associated process measurements, taking advantage of planned dam removals (e.g. Curtis Pond Dam in Danvers, MA) and culvert replacement within the watersheds (Beth Lambert, MA DER, pers. comm.), as well as our own targeted beaver dam removal. We will take upstream-downstream measurements of physical, biogeochemical and fish characteristics for one year prior to manipulation. Downstream measurements will include a longitudinal transect to determine how effects are attenuated over distance. We will measure geomorphological characteristics, establish continuous monitoring of stage/discharge, conductivity, dissolved oxygen, and temperature using existing data loggers, and collect monthly nutrient grab samples similar to that conducted at our long-term monitoring sites. Storm sampling will be conducted once per season using autosamplers. Whole stream metabolism measurements will be conducted using the single station method and periodic propane gas evasion measurements (Bott 2006). We will use solute additions with conservative tracers to characterize vertical connectivity, residence times and reactivity before and after the manipulations (Briggs et al. 2009; Briggs et al. 2010; Gooseff et al. 2011); Fig. 2.4a). Nutrient addition methods (Covino et al. 2010) will be used to quantify nutrient reactivity within targeted habitats. Preliminary application of this method to ponded floodplain habitats was successful (Fig. 2.15).

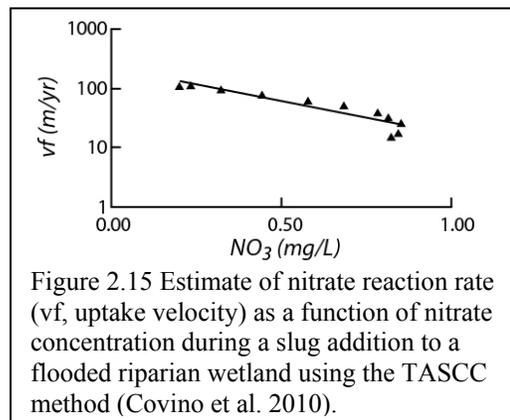


Figure 2.15 Estimate of nitrate reaction rate (v_f , uptake velocity) as a function of nitrate concentration during a slug addition to a flooded riparian wetland using the TASCC method (Covino et al. 2010).

Fish distribution associated with habitat patches in altered and control reaches will be quantified to assess the role of discontinuities on consumer biodiversity and relationships among biogeochemistry and higher trophic levels (Smith & Mather 2011). Connectivity of fish habitats will be quantified through estimates of movement across various interfaces by tagging fish of selected species with unique tags. Fish habitat quality for feeding and spawning will be determined by assessing physical conditions in habitat patches (Smith & Mather 2011).

Modeling. We will use the river network modeling framework introduced above (Fig. 2.5) to evaluate the role of patch arrangement and connectivity in regulating watershed material fluxes. The spatial data sets will be used to parameterize the number, distribution, and size of patch types embedded in the network (e.g. Stewart et al. 2011). The magnitude and location of sources will be based on land use attributes, the

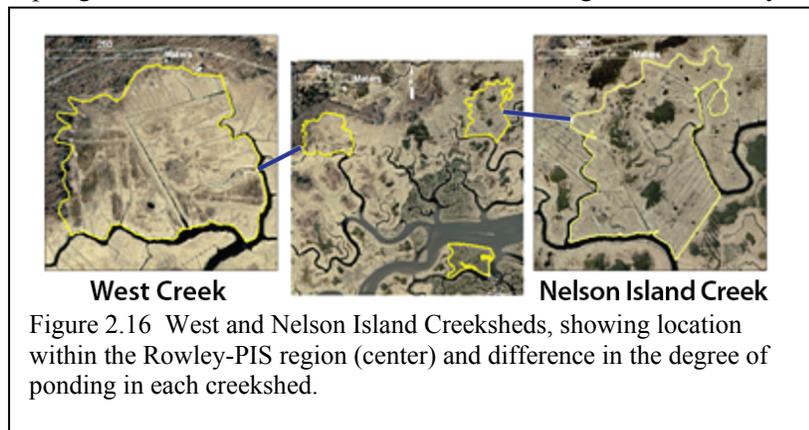
location of impervious surfaces, green space, population, and septic systems, as well as headwater biogeochemical surveys (see Q1A). Results from process measurements will constrain parameter values on hydrologic connectivity and reaction rates (Fig. 2.5a). The model will be run using early 1990's and present patch distribution to determine how the distribution and whole network regulation of materials has changed. We will conduct seasonal synoptic surveys to test spatially distributed model results given the distribution of discontinuities during the current study period (e.g. Helton et al. 2011; Wollheim et al. 2008a). We will calculate measures of model performance to estimate uncertainty for each biogeophysical characteristic (Legates & McCabe 1999) and conduct Monte Carlo analyses to explore sensitivity to various model parameters and drivers (Stewart 2009; Stewart et al. 2011).

Q2B. How do changes in riverine inputs, marsh productivity, and sea level interact with the arrangement and connectivity of patches in the estuarine seascape to influence C and N biogeochemistry?

Hypotheses: 1) As the marsh transitions from a high elevation S. patens marsh to a lower elevation S. alterniflora marsh, tidal creek drainage densities will increase and there first will be an expansion followed by a loss of marsh ponds. 2) As creek bank edge increases there will be an increase in creek bank drainage which will increase: a) the export of inorganic and organic C from the marsh to tidal waters, b) aquatic system respiration, c) aquatic net heterotrophy, and d) denitrification.

Rationale – Much of our previous work has focused on examining how seasonal and spatial differences in water residence time, salinity, nutrients, and organic matter sources control aquatic ecosystem structure and function along the mainstems of Plum Island estuaries (Vallino & Hopkinson 1998; Vallino et al. 2005; Giblin et al. 2010; Weston et al. 2010; Holmes et al. 2000; Hughes et al. 2000, Fig. 2.2). By analyzing differences between neap and spring tidal cycles we can demonstrate how coupling between tidal water and the marsh platform impacts estuarine aquatic metabolism. Following spring tides, when connectivity between the water column and the marsh is greatest, estuarine aquatic metabolism is greatest and net heterotrophy increases. Denitrification should be greatest during spring tides since advection through porous creek banks is proportional to tidal range and creek bank denitrification rates are several times higher than either the marsh platform or the creek bottoms. The impact of the marsh on estuarine metabolism is most obvious in the mid-reaches of the mainstem where the marsh:water ratio is highest and residence time is longer than a few days. Our recent work shows large changes in marsh:water ratio, creek bank drainage density and the size and area of marsh ponds are occurring in PIE marshes. These geomorphic changes will affect the coupling between tidal waters and the marsh throughout the estuary and therefore alter estuarine C and N biogeochemistry in fundamental ways.

During the last half of the 20th century there have been dramatic changes in relative size and arrangement of marsh and tidal creek patches in some of the seaward portions of the estuary, especially in the Rowley River marshes adjacent to Plum Island Sound. The extent of these changes can be seen



by comparing two creeksheds within the Rowley region: a) Nelson Island Creek, which is most removed from terrestrial inputs of sediments and nutrients and b) West Creek, which is adjacent to uplands and likely to receive greater local sediment inputs (Fig. 2.16). Nelson Island Creek shows large changes since 1952 (Fig. 2.17), whereas West Creek remains relatively unchanged. Important differences between the Nelson and West marshes today include (respectively): relative areas of marsh: water (6:1 vs. 25:1), tidal creek drainage density (40 to 14 m/ha), pond surface area density (33 to 3 m² / ha), and pond size (34 to

21 m²). We interpret these geomorphic changes in the Nelson marsh /creek system to be the result of rates of sea-level rise that are too high relative to modern rates of sediment supply. These changes are consistent with MEM which predicts a decrease in marsh elevation and a transition from *S. patens* to *S. alterniflora* in the new lower elevation marshes. They may be indicative of an overall system response or evolution to RSLR (perhaps degradation in the sense of Reed 1995; Kirwan et al. 2010). We predict that connectivity between marsh and the water column will be much stronger at Nelson than at the West marshes with large implications for the biogeochemistry of these two systems. We expect to see more C export, more water column respiration, greater net heterotrophy, and more denitrification at Nelson.

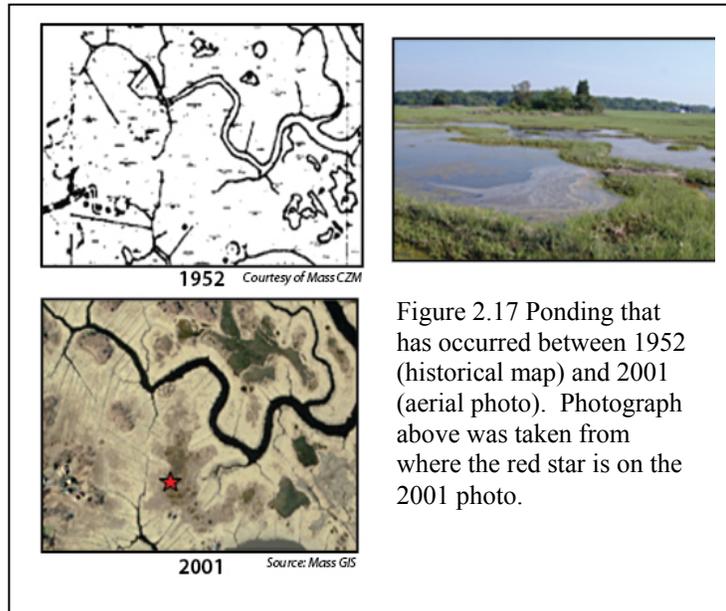


Figure 2.17 Ponding that has occurred between 1952 (historical map) and 2001 (aerial photo). Photograph above was taken from where the red star is on the 2001 photo.

Approach - We will continue long-term monitoring along the mainstem of the estuaries to address our long-standing questions about the effects of climate change, land-use change, and sea-level rise on estuarine aquatic C and N biogeochemistry. Currently the effects of varying riverine inputs are seen most readily in the upper 5 km of the estuary, the effects of varying marsh:water coupling in the mid-estuary, and the effects of varying ocean productivity in the lower estuary – Plum Island Sound. The most dramatic changes in the marshes are occurring in the most seaward portion of the estuary but their effects on aquatic metabolism are difficult to detect in the mainstem using free water measurements because residence time is extremely short. We will add new effort in PIE IIIB using a space for time substitution approach comparing C and N biogeochemistry in two tidal creek systems that differ in their degree of ponding and drainage patterns: West Creek (static) and Nelson Island Creek (evolving rapidly).

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 O₂ instrumentation. These measurements are supplemented with dawn/dusk oxygen and DIC transects along the complete length of the estuary over multiple full tidal cycles in spring (high river flow) and in late summer (low flow) where we also measure nutrient chemistry, chlorophyll biomass and plankton community composition in the water column. Benthic metabolism, the exchange of nutrients between the sediment and the water, and sediment N dynamics are measured at several locations along with benthic chlorophyll and sediment C and N content. Creek bank drainage is monitored continuously at two sites using instrumented wells and the chemistry of the draining water is monitored using diffusion samplers deployed monthly. New studies: At the creekshed scale, we will conduct paired metabolism and flux measurements in the major creeks draining/flooding the two contrasting marsh systems. We have already begun some measurements at Nelson Island marsh and creekshed and plan to begin monitoring West Creek marsh and creekshed in spring of 2012. We will measure conductivity, temperature, dissolved oxygen, colored dissolved organic matter (CDOM), and pH continuously, and discretely sample for DIC, alkalinity, and particulate and dissolved organic carbon in order to quantify the concentrations of C entering and leaving the creekshed system and to estimate rates of aquatic system metabolism. Continuous measurements of pCO₂ will be included if other funding becomes available. Initial data (Raymond unpublished) shows good correlations between in-situ CDOM measurements and grab samples of DOC. We will measure water flux from these same creeks in order to calculate mass flux of C and O, and, after correcting for air-sea fluxes, to calculate metabolism. From LIDAR and kinematic GPS data, we will develop maps of the extent of marsh flooding within the

creekshed, which varies from being relatively small during neap tides to complete during spring tides. We will combine these horizontal measures of exchange of materials with flood waters with the vertical measures of exchange between marsh and the atmosphere using the eddy flux tower to obtain a relatively complete C balance for each of the two systems.

Although we will only measure whole system fluxes using flux towers at the creekshed level in two locations, we will make additional measurements of creek metabolism and horizontal fluxes at smaller scales to help extrapolate our results. We will identify 6 creeks that differ in their connectivity to the marsh platform. In each we will deploy continuous oxygen and current sensors for several tidal cycles each month and autosamplers will be used to collect water samples for carbon analysis as described above. We will measure pond metabolism to quantify the importance of peat decomposition in contributing to pond deepening by deploying O₂ meters seasonally over spring/neap tidal cycles. By comparing the increase in elevation of the adjacent marsh to pond elevation we can compare the relative importance of marsh building to pond peat decomposition in pond deepening.

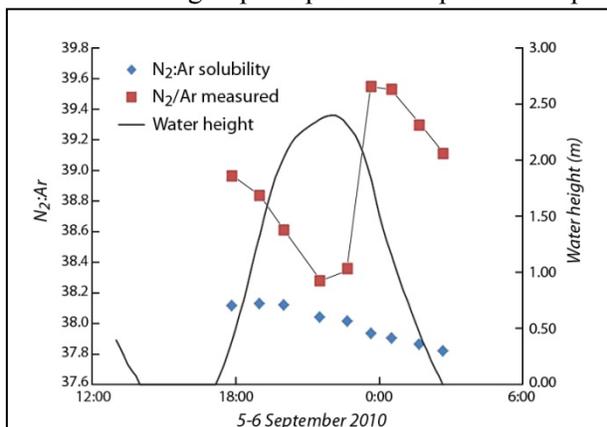


Figure 2.18 N₂/Ar in water draining a fertilized tidal creek (red) compared to the ratio expected from equilibrium with the atmosphere (blue). The nearby control creek showed values very close to atmospheric equilibrium. The "excess" N₂ suggests that creek banks are hot spots for denitrification.

We are also interested in how different marsh/creek/pond configurations affect whole system denitrification and N cycling. In conjunction with horizontal flux measures in the tidal creeks, we will seasonally assess denitrification by sampling N₂/Ar concentrations in discrete water samples collected over several tidal cycles. We have successfully done this in the fertilized creeks (Fig. 2.18) and have data suggesting that creek banks are denitrification hot spots. If so, sites with the greatest creek bank:water ratio should show the highest overall denitrification rates. Modeling and scaling up: We will use our hydrodynamic model that fully captures the spatial configuration of the estuarine seascape to extrapolate our biogeochemical and metabolic understanding from the creeksheds and estuarine mainstems of the entire estuarine and marsh system. We developed PIE-FVCOM in the last funding cycle, based on UMass

Dartmouth's 3D Finite-Volume Coastal Ocean Model (FVCOM: Chen *et al.* 2003; Chen *et al.* 2004). We extended the domain of our model to incorporate the lower portion of the Merrimack River, as well as the coastal ocean that connects the Merrimack to the southern entrance of PI Sound (Fig. 2.19) and used PIE LIDAR data combined with georeferenced depth soundings to construct a high accuracy marsh topography-bathymetry digital elevation model (Fig. 2.20). As an example of marsh-water interactions, PIE-FVCOM predicts that the marsh platform alters tidal harmonics such that water holdup within the system occurs with a 3 day periodicity (Zhao *et al.* 2010). This indicates that flux-balancing constituent transport in our system will require averaging over periods longer than one tidal cycle. We have not experimentally verified this, but plan to do so in this funding cycle.

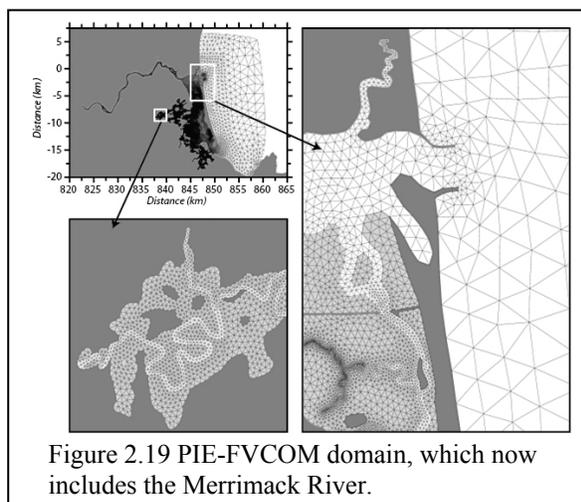
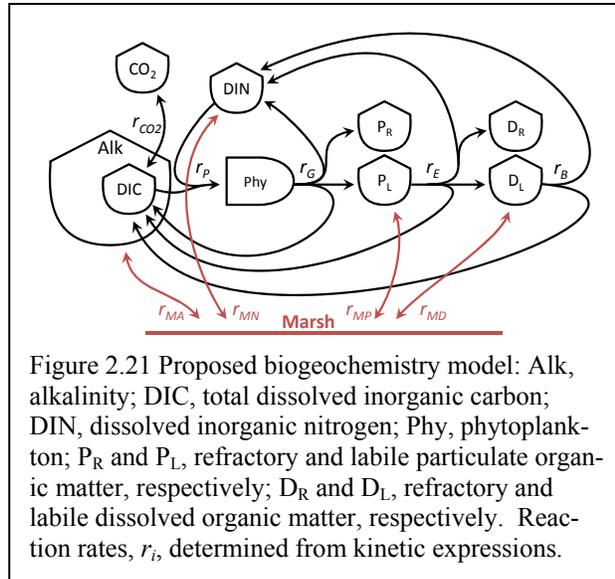
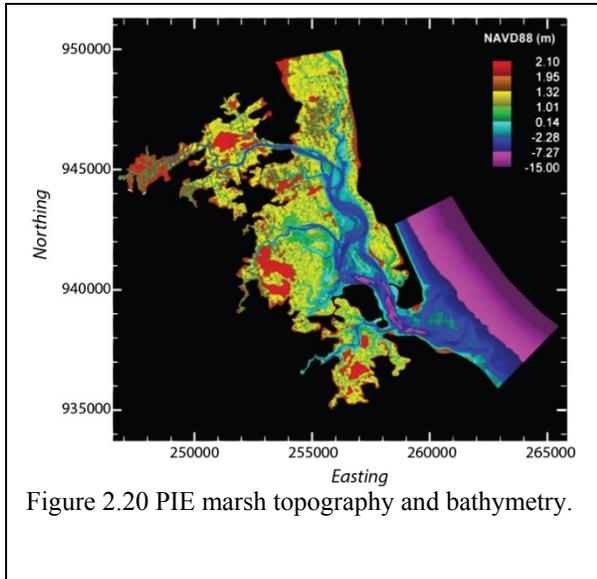


Figure 2.19 PIE-FVCOM domain, which now includes the Merrimack River.

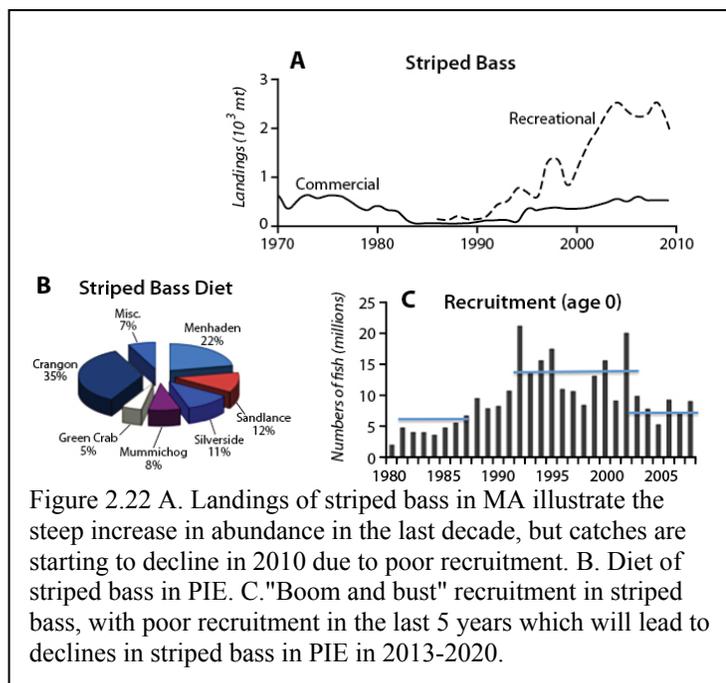


We also plan to examine carbon storage, transport and transformation within PIE by developing a minimal parameter carbon model (Fig. 2.21) that will be calibrated from field observations discussed above. The major processes we will incorporate include air-water gas exchange, carbonate chemistry, N-limited phytoplankton growth, particulate and dissolved organic matter transformations, and production or consumption of the associated state variables across the marsh-sediment-water boundary using first order approximation models (Vörösmarty & Loder 1994). By coupling this model with PIE-FVCOM we will be able to examine spatial and temporal C and N sources and sinks in scales ranging from small creeksheds to entire estuaries and the coastal ocean. Model calibration will rely on PIE long-term observations, as well as data from our paired watersheds.

Question 2C: What are the implications of the configuration and connectivity of different habitat patches and changing drivers on spatial variations in food webs across the estuarine seascape?

Hypotheses 1) Salt marsh and open bay food webs are integrally linked through trophic subsidies and by reciprocal top-down control across habitats by predators; 2) Long term watershed or climate changes that decrease river inputs will de-couple benthic and pelagic energy pathways in upper estuarine food webs by limiting pelagic algal production, but will have little effect in the more benthic-supported lower estuary.

Rationale: Understanding the relationships between abiotic and biotic controls on food-web structure, trophic diversity and ecosystem function is crucial in the face of anthropogenic environmental changes (Hooper et al. 2005; Duffy et al. 2005). Fundamental questions remain about how productivity, disturbance and habitat configuration influence food-web structure and how these controls might



vary across the landscape remain for most systems (Post 2002; Layman et al. 2007; McCann & Rooney 2009; Sargeant et al. 2010; Massol et al. 2011).

Observations from our long-term LTER data suggest that spatial linkages among habitats via mobile consumers (fish and shrimp) provide trophic subsidies from salt marshes to top predators, such as striped bass, in adjacent open bay food webs. The data also indicate that striped bass exert important top-down controls on fish and shrimp, which in turn may control lower consumers in salt marsh food webs. Support for these ideas come from our observations on striped bass and fish and shrimp at PIE. The coastal migratory population of striped bass in MA has increased almost an order of magnitude since the 1980s driven primarily by successful recruitment during the 1990's (Fig. 2.22A). Bass actively feed on small salt marsh-associated mobile intermediate consumers such as mummichogs (*Fundulus heteroclitus*), and

shrimp (*Palaemonetes sp.*) (Ferry & Mather 2012; Fig. 2.22B) suggesting a potential trophic subsidy from salt marshes to open bay food webs (Deegan 1993). We have measured a 10-fold decline in these intermediate consumers that coincides with the steeply increasing abundance of striped bass (Fig. 2.23). These patterns are consistent with theories that suggest trophic subsidies from high to low productivity areas (Huxel & McCann 1998; Flecker et al. 2010) should have the greatest impact in the marsh since marsh productivity is approximately 10-fold higher there than in adjacent open bay areas. Our finding of distinct, small foraging areas for individual striped bass at salt marsh creek mouths (Pautzke et al. 2010), suggests that striped bass behaviorally adjust their 'realized' ecosystem to maximize growth and this 'smaller realized ecosystem' may result in stronger top down control (McCann & Rooney 2009). We propose to test these mechanistic connections, as well as continue long-term monitoring of key species at different trophic levels.

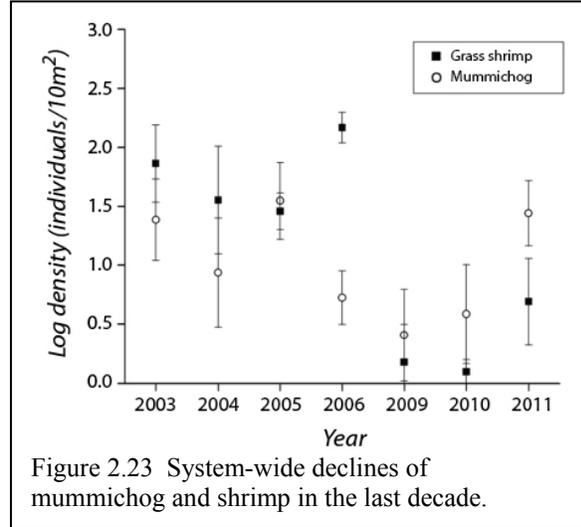


Figure 2.23 System-wide declines of mummichog and shrimp in the last decade.

Our long-term isotopic measurements of key functional groups illustrate how trophic diversity, trophic similarity, breadth of basal resources ($\delta^{13}\text{C}$ range) and vertical trophic position ($\delta^{15}\text{N}$) vary spa-

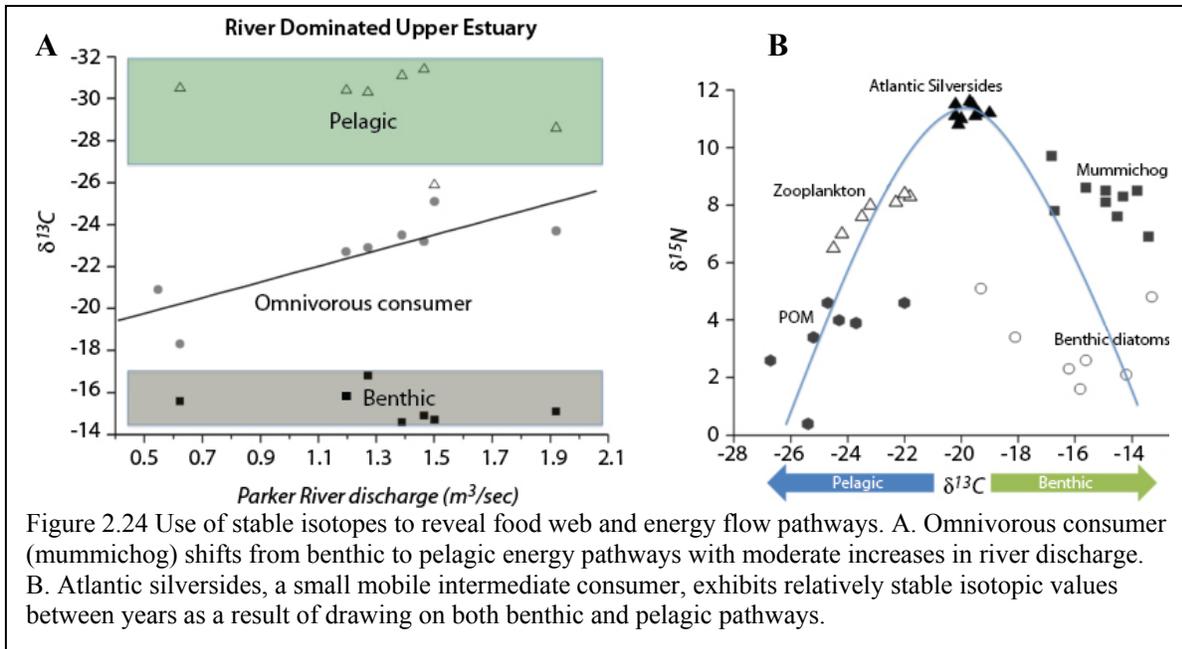


Figure 2.24 Use of stable isotopes to reveal food web and energy flow pathways. A. Omnivorous consumer (mummichog) shifts from benthic to pelagic energy pathways with moderate increases in river discharge. B. Atlantic silversides, a small mobile intermediate consumer, exhibits relatively stable isotopic values between years as a result of drawing on both benthic and pelagic pathways.

tially and temporally in the estuary and how these functional groups respond to changes in ecosystem drivers (Deegan & Garritt 1997; Fig. 2.24). Isotopes reveal that many salt marsh intermediate consumers (e.g., polychaetes, tanaids and harpacticoid copepods) use high quality algal resources rather than the more abundant, but low quality salt marsh detritus (Deegan & Garritt 1997; Buchsbaum et al. 2009; Galván et al. 2008; Galván et al. 2011) supporting theories that consumers seek “quality over quantity” (Marecchelli et al. 2011). This suggests that environmental changes that alter algal production, such as changes in marsh flooding (Deegan et al. 2000), freshwater discharge (Hughes et al. 2000) or nutrient availability (Deegan et al. 2007), will have a disproportionate impact on energy flow through food webs. We also use stable isotopes to determine flows through benthic and pelagic pathways (Fry et al. 2008; Fig. 2.3; 2.25). For example, in the upper estuary, resource use by mummichogs, shifts from benthic to pelagic energy pathways with moderate increases in river discharge (Fig. 2.24A). Mobile species higher in the food web have the potential to stabilize food webs by integrating production across the landscape (Rooney et al. 2008; McCann & Rooney 2009). Atlantic silversides, a mobile intermediate consumer, exhibits relatively stable isotopic values among years as a result of drawing on both benthic and pelagic energy pathways (Fig. 2.24B).

Approach: We will test the hypothesis that trophic subsidies provided by mobile prey (mummichogs, shrimp) that seasonally move between marsh and open bay patches support top predators in less productive open bay ecosystems. We currently estimate the abundance, biomass, and movement of these small fish and shrimp from the marsh using flume nets supplemented with fyke nets in creek channels. To assess the potential importance of these small consumers to top predators, we will compare their energy flows from the salt marsh to estimates of top predator consumption needed for measured growth using bioenergetics modeling of striped bass (Fish Bioenergetics Model 3.0; parameterized for striped bass, Hartman & Brandt 1995; Ferry & Mather 2012). Striped bass growth will be estimated via tag/recapture, scales and RNA:DNA (Stierhoff et al. 2009) and diet will be measured using gastric lavage (Ferry & Mather 2012).

We will test the idea that striped bass abundance feeds back on marsh function via top-down control of mummichogs. The projected declines in striped bass abundance due to low recruitment (Fig. 2.22C) will increase the abundance of mummichogs and lead to increased predation rates on salt marsh invertebrates (Fleeger et al. 2008). To assess this we will continue our long-term measurements of natural marsh food webs and abundance of consumers using flume nets for small mobile consumers and 0.15 m² quadrants for marsh epifaunal invertebrates. We have nine years of data on consumers from both reference creeks, as well as from the experimentally enriched TIDE creeks. We expect that mobile prey under strong predatory control will change their habitat use thus altering their food source and position in food webs. We will use stable isotopes to examine trophic diversity, breadth of basal resources ($\delta^{13}\text{C}$ range) and trophic position ($\delta^{15}\text{N}$) in prey species and correlate these data with striped bass abundance on an annual basis to test for effects on salt marsh food webs.

We will continue to use stable isotope data to understand changes in organic matter source, trophic position of consumers and energy flow through benthic/pelagic pathways across the estuarine landscape. Because complete isotopic sampling of an entire food web is impractical (we have identified 19 species of annelids and 38 species of copepods in the marsh alone), we have sampled 10 key functional groups whose isotopic signatures reflect trends in organic matter sources and include intermediate consumers that represent occupy diverse roles in the food web. We will add striped bass, blue fish and snowy egrets (using feathers) as highly mobile, integrating top predators to our spatially-explicit long-term ¹³C and ¹⁴N, ³⁴S isotopic surveys. Changes in the ¹³C isotope ratios of striped bass scales (Pruell et al. 2003) and bird feathers (Kelly 2000) have been related to changes in the relative proportions of pelagic and benthic food items and to changes in the feeding locations of mobile species. We will compare upper (riverine dominated) and lower (marine dominated) estuary food webs to test whether food webs are more variable in the upper estuary due to changes in discharge. We expect that drought will produce a spatial shift up-river in important marine food sources. Comparison among years of high and low RSL should show an increase in trophic subsidy from marsh to open bay during high years, resulting in a shift in ¹³C of top consumers in the open bay food web away from marine and toward marsh or benthic algal values.

Question 2D. What are the configurations of habitats, and geomorphic features and hydrodynamics, that create regions of high production and efficient energy transfer to higher trophic levels?

Hypothesis: Long-term changes in geomorphology and hydrology will alter benthic/marsh and pelagic food webs, and connections to open bay areas, with different implications for top aquatic (fish) and semi-aquatic (bird) predators. Increased marsh flooding is expected to increase small mobile intermediate consumers on the marsh surface favoring energy transfer to birds.

Rationale: Marsh elevation, which determines the frequency and extent of marsh flooding, is a key control on production of small marsh associated mobile consumers (Javonillo et al. 1997; Minello et al. 2011) that are preferred prey of many top fish and bird predators. In PIE, we found the highest mummichog growth rates in lower elevation marshes that flooded frequently (Haas et al. 2009). Our work using ¹⁵N isotopic tracers of food web flows has also shown that wide, shallow systems dominated by mudflats transfer a greater proportion of energy to higher trophic levels compared to deep, steep sided systems. Despite these findings, questions remain about how other seascape attributes influence transfer of productivity in food webs. For example, higher geomorphic complexity (e.g., higher edge to marsh) correlates with increased shrimp abundance (Haas et al. 2004) but lower growth of fish (Kneib 2009). Our understanding of controls on the transfer of productivity to large mobile predators, such as fish and birds, that move among and integrate larger and more complex habitat landscapes, is generally less well developed than that of within-habitat controls for invertebrates and small mobile consumer species (Simenstad et al. 2000). Striped bass may be favored by current conditions, while the expansion of marsh ponds and tidal flats may favor waders and shorebirds that feed in shallow water (Erwin et al. 2006).

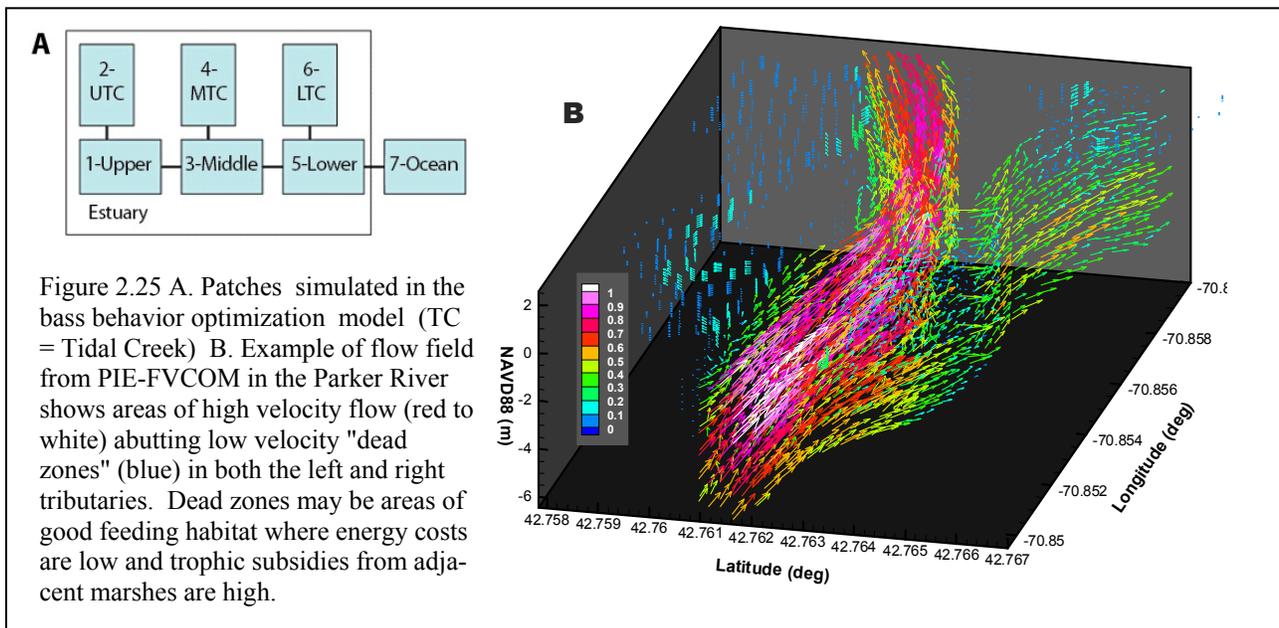
Approach: We will test hypotheses about the importance of geomorphic control on secondary production by developing a mechanistic understanding of the responses of intermediate consumers and top fish and bird carnivores to changes in marsh, creek channel and open bay configurations using a space for time substitution and our nutrient-enriched creeks undergoing rapid change. We will continue our core measurements of abundance of mobile consumers and small invertebrates in tidal creeks of different configurations (Q2B) and in experimental creeks (Fig. 2.23; Deegan et al. 2007). Our nutrient-enriched creeks are losing the low marsh creek edge habitat critical to small fish and shrimp and mudflats are expanding (Deegan et al. submitted). After 8 years, most intermediate consumer biomass has been shunted into *Ilyanassa*, a long-lived snail which is less consumable due to its strong shell (Johnson & Short, in review). These snails are generally not available to the dominant small nekton (mummichogs and grass shrimp); thus changes in geomorphology and energy flow are creating a “trophic bottleneck”. Loss of low marsh edge habitat combined with food web changes induced by nutrient enrichment are predicted to result in declines in fish and shrimp and thus a decrease in the annual export of secondary production to the open bay. We will determine the relative importance of loss of edge habitat versus food web changes by comparing across systems at different stages of landscape evolution. By comparing the growth and abundance of consumers from the Nelson Island marsh to that of the West Creek marsh (Q2B) we can examine the impacts of flooding regime, ponding, and higher creek density on secondary productivity. We will also conduct short-term experiments to establish marsh-flooding requirements for major consumers (*Fundulus*, *Menidia*, *Palaemonetes*, and *Crangon*).

We will use stable isotopes to determine organic matter sources and food chain lengths in different geomorphic settings. Modeling - We will use inverse food web modeling (Deegan et al. 1995; Soetaert & Van Oevelen 2009; van Oevelen et al. 2010) constrained by stable isotope analysis to look at the efficiency of production, and transfer of energy to intermediate consumers such as annelids, snails, and small mobile consumers. Results will be related to marsh flooding, habitat complexity (Whaley et al. 2007), organic matter source, and diet, and integrated into our individual-based model of mummichogs.

We will use measures of geomorphic features coupled with behavior models for a top predator, striped bass, to understand and predict the effects of seascape change on productivity and efficiency of energy transfer. We will use the change analysis described in Q2B to measure the characteristics of creeks (width, low tide depth of remaining water), and the extent of tidal flats and marsh ponds to determine whether creeks are widening due to recent erosion. We will couple topographic features from the 2011 LIDAR and updated bathymetry maps with our new high resolution 3D PIE-FVCOM model to examine

hydrodynamic flow fields at specific locations to characterize potential habitats for striped bass (Fig. 2.25). New acoustic tag monitoring approaches (Cooke et al. 2004) provide 3D locations of striped bass that can be compared to flow fields at the same location/time. By correlating striped bass presence to flow fields and bathymetry we will develop hydrodynamic/geomorphic “rules” that can be used in the individual-based modeling that is being developed for higher trophic levels. Diet and growth (see above) will also be assessed. Modeling - To determine if foraging movements of individuals across habitats of different foraging profitability intensify or dissipate their trophic impact, we will use our newly developed dynamic behavior model (Fig. 2.25) that predicts the consequences of movement for consumption and growth. We will compare these model results to the bioenergetic model (Q2C).

Our examination of the influence of geomorphic features on birds will focus on Snowy Egret (*Egretta thula*) as a representative semi-aquatic predator species that is common at PIE and shows a preference for two of the most abundant consumers influenced by marsh configuration (mummichogs and shrimp; Parsons & Master 2000). Wading birds are sensitive to prey abundance and geomorphological features that provide access to feeding areas (Master et al. 2005; Pierce & Gawlik 2010). Snowy egrets favor shallow ponds with depths less than 20 cm and with relatively high prey concentrations (Master et al. 2005). Steep



sided marsh creeks provide little opportunity for foraging by egrets or other wading birds or shorebirds (Clarke et al. 1984). More ponds on the marsh surface and increased productivity of small fish and shrimp in response to increased marsh flooding should provide greater feeding opportunities for these birds at least in the short term. Eroded creek banks that result in expanded tidal flats should also enhance feeding opportunities as was the case for sandpipers on our nutrient enriched sites (Johnson et al. 2009).

We will quantify abundances of snowy egrets using weekly surveys and correlate this with habitat characteristics, bird activity and species counts of other waders or shorebirds in the same area. We will compare geomorphic attributes with foraging success. To assess the effects of increased ponding on birds, we will measure the depths and sizes of salt pannes and pools favored by birds compared to those not used by the birds. We will correlate avian use with sediment, geomorphic and landscape characteristics (Gawlik 2002; Granadeiro et al. 2003; Trocki & Paton 2006; Raposa et al. 2009). Modeling – We will use spatial regression models to determine the relative importance of local vs larger-scale geomorphic configurations to address the question of how a wetter marsh with more heavily eroded creeks and greater pond density may impact bird predators.

Q2E. Do microbial systems organize towards a state of maximum entropy production (MEP), and can this principle be used to understand estuarine biogeochemistry in a spatially complex seascape?

Hypotheses: 1) Models based on MEP will provide more robust predictions than models lacking such fundamental constraints, especially when models are required to extrapolate beyond the dataset used to calibrate them. 2) Living systems have evolved cooperative networks that operate over space so as to maximize entropy production globally over the relevant ecosystem domain.

Rationale: Currently, estuarine biogeochemistry is described as a set of chemical reactions carried out by organisms competing for resources. Under this paradigm, biogeochemistry depends strongly on which organisms are present and their interactions, so predictions are site specific and difficult to extrapolate. An alternative approach for understanding biogeochemistry is provided by the maximum entropy production (MEP) principle (Dewar 2003, 2005, 2009). We have postulated that the MEP principle describes biogeochemistry that results from microbial communities that form distributed metabolic networks (Vallino 2010). The basic MEP conjecture is that systems with many degrees of freedom will organize to maximize the rate of entropy production, which is equivalent to maximizing free energy dissipation rate. For reaction networks (biological or otherwise) where the free energy released is not stored in formation of other energy potentials (i.e., gravitational, mechanical, electromagnetic, etc), entropy production, $\dot{\sigma}$, is given by $-r \Delta_r G/T$, where r is reaction rate, $\Delta_r G$ is the Gibbs free energy of reaction and T is temperature (Eu 1992 pp. 131-141). To develop an MEP-based model, we view biogeochemistry as a network of autocatalytic reactions where microbes serve as the catalysts, \mathcal{S} .

The biogeochemical reactions that occur in a given environment depend on the distribution and abundance of the microbial catalysts. For example, consider the aerobic and anaerobic oxidation of polymeric carbohydrates, $(C_6H_{12}O_6)_n$, illustrated in Fig. 2.26, where the concentration of catalyst for a given reaction i , is given by \mathcal{S}_i . Typically, emphasis is placed on understanding the growth behaviors of individual microbes or guilds (i.e., \mathcal{S}_i), where the nuances of their growth kinetics and interactions define the overall biogeochemistry. While this reductionist approach has many advantages, namely that it is ultimately how systems are organized, it has the disadvantage that a great deal of information is required on individual growth kinetics and predatory tactics of each organism in the network, which may be comprised of 100's to 1000's of different "species". Furthermore, it is a purely descriptive approach that lacks any governing principles other than conservation of mass. If, however, systems organize towards MEP, we can determine how catalytic activity should be allocated based on maximizing entropy production subject to resources (N, P, S, etc.) needed for catalyst synthesis.

To extend MEP to transient systems that are of more biogeochemical interest, we have proposed a conjecture that distinguishes living systems from abiotic systems such as fire: *Information stored in the genome allows living systems to anticipate future states (based on past events) allowing them to produce more entropy (dissipate more free energy) than nonliving systems that maximize entropy production instantaneously* (Vallino 2010). We developed an optimal control algorithm to solve these problems where entropy production averaged over a characteristic time scale is maximized. We are now examining how MEP applies to systems involving one or more spatial dimensions.

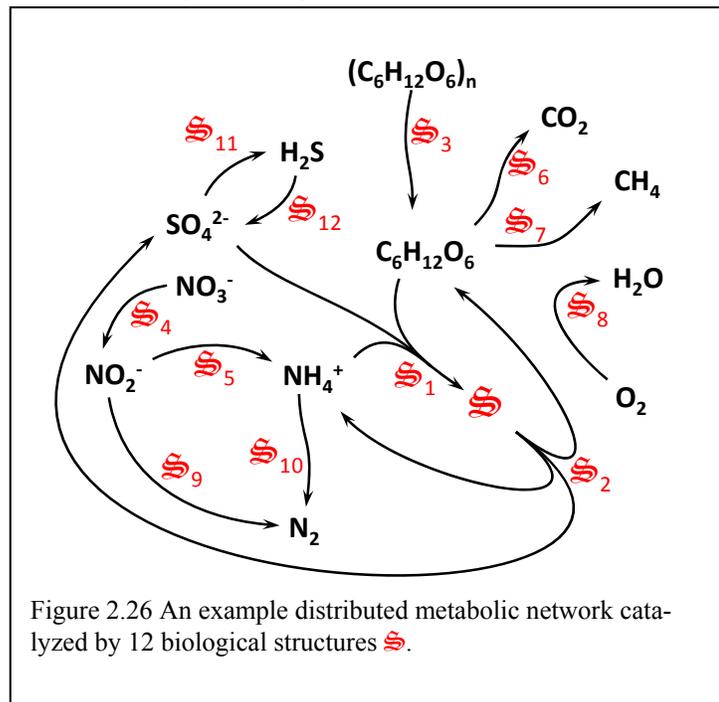
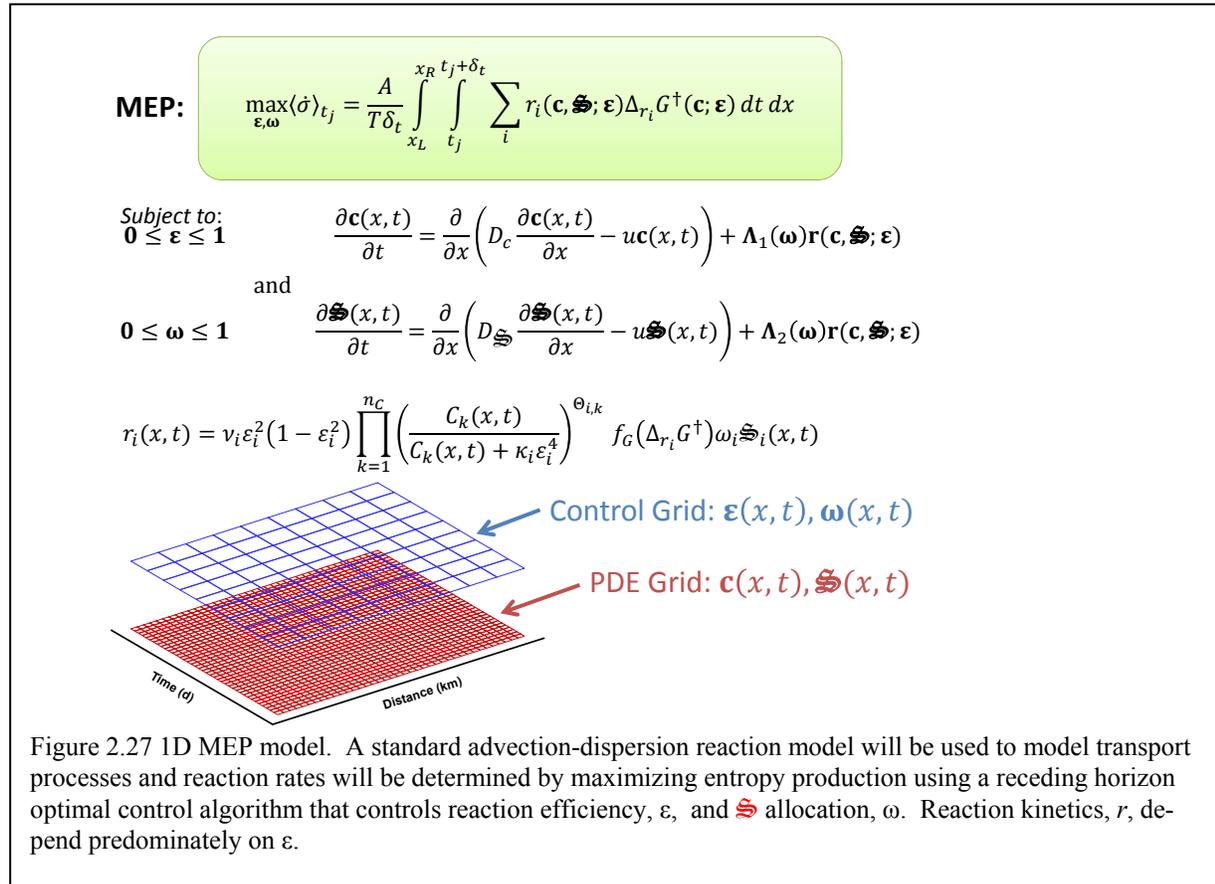


Figure 2.26 An example distributed metabolic network catalyzed by 12 biological structures \mathcal{S} .

Entropy production can either be maximized at each point in space (local maximization), or maximized over the system domain (global maximization). Results show that maximizing entropy production globally can exceed entropy production when maximized locally, but this requires spatial coordination and some form of communication (such as microbial quorum sensing (Keller & Surette 2006; Shank & Kolter 2009)). The results also illustrate the importance of choosing the model system boundaries, because incorrectly isolating subsystems will result in local optimization instead of global optimization (Vallino 2011). **Approach:** We propose to develop a 1D MEP-based model to describe estuarine biogeochemistry based on our current theoretical hypotheses and new numerical techniques for solving associated optimal control problems. To test Hypothesis 1 we will develop two 1D models, each coupled to a 0D sediment model that will use contrasting approaches to predict aerobic and anaerobic reaction rates (CO₂ fixation, aerobic respiration, denitrification, sulfate reduction and sulfide oxidation, (Fig. 2.26) along the Parker River and PI Sound. The conventional model will use the organism perspective (i.e., food web model) and will be similar to models we have previously developed (Hopkinson & Vallino 1995; Vallino 2000; Vallino et al. 2005). The MEP-based model will use the distributed metabolic network perspective (Fig. 2.26) where synthesis and allocation of biological structure is governed by maximizing entropy production over time and space. We will also use a recently developed Monod-like reaction kinetics model that depends almost entirely on growth efficiency (Fig. 2.27) (Vallino 2011). The new approach allows us to place almost all model degrees of freedom in the optimal control variables, so the MEP model will have very few adjustable parameters. Both the MEP and conventional models will be calibrated with PIE data on productivity, dissolved oxygen, and nutrients and tested against a second set of observational data not used for calibration. We hypothesize the MEP-based model will outperform the conventional model when challenged with new observations. To test Hypothesis 2, we will compare observations to model predictions from our MEP model based on local versus global entropy maximization (Vallino 2011). We



expect that entropy production based on global optimization will exceed that from local optimization and will more closely match observations.

We currently have been using our MEP-based approach to examine metabolic switching between anammox and denitrification, anaerobic carbon oxidation and methanotrophic communities (Vallino 2010), all of which are showing promising results. However, we have found that solving the associated control problem can be very computationally intense even when we use a much coarser grid for the control variables (Fig. 2.27), so we have developed a parallel version of the algorithm for the 1D case. Ultimately our objective is to develop an MEP-based model that can run in 3D simulation environments, such as in our PIE-FVCOM model. One approach to solving the computational challenge is to use a Darwinian-type model (Follows et al. 2007; Follows & Dutkiewicz 2011) in which the simulated organisms that populate the model solve the MEP optimization problem as a result of their interactions and competition. The challenge in this modeling approach will be to use MEP as a basis for assigning functional traits to modeled organisms. While the Darwinian-type approach is not guaranteed to arrive at an MEP solution, we expect the solution to be close to an optimal one, which is still consistent with MEP theory that is based on probabilistic, not deterministic, outcomes (Lorenz 2003).

2.5 INTER-SITE COMPARISONS - There are four Atlantic Coast marine sites (PIE, VCR, GCE, FCE) within the LTER network. In addition to spanning a latitudinal gradient they differ in key features including land use, freshwater inflow, tidal amplitude and the rate of relative sea-level rise. These sites are all making a number of the same key measurements needed to understand how marshes will respond to sea-level rise. To promote synthesis we plan to meet annually to advance cross-site collaborations. Meetings will rotate among the sites, and will be held in conjunction with site annual meetings. Visitors will attend the annual meeting of the host site, and then meet to address topics ripe for cross-site work. Initial topics of synthesis include: 1) controls on wetland accretion, 2) measuring lateral C fluxes in coastal wetlands, 3) controls of coastal plant productivity, and, 4) food web dynamics. We will also bring in comparative work from other marshes where appropriate. Currently PIE scientists are also collaborating on a number of LTER cross site comparisons on hydrology (Wollheim), lawns (Polsky), land change (Pontius), carbon storage (Neill), fertilization studies (Morris), and data management (Garritt).

PIE will be home to a relocatable NEON tower in the suburban end of the wild-lands to urban gradient of the Northeast site; this tower will have an aquatic array. Wil Wollheim is a member of the NEON Aquatic Technical Working Group and Giblin is on the NEON DSECC. Mather and Deegan participate in the Atlantic Telemetry Network where investigators using acoustic tags share data so a complete picture of striped bass migration can be obtained. Giblin and Neill are participating in the Northeast Science & Stewardship Collaborative which includes 4 LTER sites and other institutions in the northeast with common interests in science and policy.

3.0 OUTREACH AND EDUCATION PROGRAMS

The specific goals of the PIE-LTER's educational and outreach activities vary with the target group but always include an emphasis on the importance of long-term data to understand ecosystem change.

K-12: Our goals are to: 1) excite students and their teachers about coastal science by hands on activities, 2) encourage students to consider a career in science, and, 3) promote environmental stewardship. We will continue to try to expand our highly successful LTER Schoolyard program which is the result of collaboration with Mass Audubon. Mass Audubon has implemented, with major support from the LTER, "The Salt Marsh Science Project" (SMS) (<http://www.massaudubon.org/saltmarsh>) a 5th–12th grade education program. The key aspect of this program is a hands-on experiential program in the student's own backyard. Students investigate how marsh vegetation and fish communities in their town are changing and compare their data to data collected by students in previous years. The studies have been designed by our education coordinator Elizabeth Duff (Mass Audubon), in conjunction with PIE and other scientists. SMS serves an average of 1000+ students per year and 50 teachers from 10 schools per year. For the past two years in a row Ms. Duff has been honored for her work, last year being awarded the prestigious "Massachusetts Marine Educator of the Year" Award. During PIE II Duff also launched a partnership with the Fish and Wildlife service to eradicate the invasive perennial pepperweed

<http://www.fws.gov/northeast/parkerriver/pepperweed.html>. This effort has grown and has now involved over 1,000 youth and adult volunteers. Duff and Giblin both work with the Gulf of Maine Institute (GOMI) to involve youth in environmental stewardship projects and this has expanded since GOMI and local schools have launched an initiative on “place based education”. Duff has worked with PIE scientists developing a curriculum on bass (<http://www.massaudubon.org/saltmarsh/stripes/>) and we are seeking funds to produce more content such as this. We will also continue to work with the Governor’s Academy (GA) where students monitor mussels and intertidal marsh plant distribution as part of their regular science program. They maintain a long-term dataset which we post on our web site. In addition, 2-3 students per year are given paid internships to participate in PIE research. This coming year a GA high school teacher and 2 high school students will be involved in research that examines how aquatic animals at PIE respond to changes in watershed characteristics, climate, and geomorphic structure in order to bring knowledge of coastal ecosystem science into their classrooms. Finally, PIE scientists Colin Polsky and Abigail Kaminski will complete their book for the LTER children’s book series this year. The book is called: “Bradley and Emma and the Lawn Mystery”.

Undergraduate, Graduate and Post-Graduate Education: The goal of our undergraduate education program is to give students a high quality hands-on research experience. Summer students spend part of their time working on PIE-LTER projects while developing an independent research project. In collaboration with the MBL-SES program, 1-4 students per year do their five-week independent project at PIE. In all cases students collect and analyze their own data and make an oral or written (and often both) presentation on their work. In some cases they continue this as an independent senior thesis at their home institutions. We encourage and financially support students to make presentations at regional scientific meetings and a number have received best student paper awards. A number of these undergraduate research projects have also been written up in scientific publications. Through PIs Pontius and Polsky we will continue to have both undergraduate and graduate students participate through the Clark University NSF REU Site “Human-Environment Regional Observatory (HERO)” (<http://hero.clarku.edu>).

Our graduate student population has greatly expanded with the new MBL-Brown partnership. A new Integrative Graduate Education and Research Traineeship (IGERT) grant, on which Giblin is a co-PI, provides fellowships for incoming Brown graduate students to link microbial processes and ecosystem biogeochemistry at PIE and other LTERs. Last fall these students made field trips to PIE and developed a joint research project in “reverse ecology” for this year. Since 2006, ten post-doctoral students directly worked on PIE-LTER research questions and eight have been affiliated with other projects doing at least some of their research at PIE. Along with the other three Atlantic coastal sites (VCR, GCE, FCE) we will collaborate to teach a graduate course that will feature readings and lectures from PIs at all four LTER sites. The course will span a range of disciplines in both natural and social science, and provide experience in accessing and analyzing long-term data sets.

Outreach: Our goal is to increase the environmental knowledge of the general public, especially on issues related to watershed, estuarine and marsh processes. We have done and will continue to do this by giving presentations to local NGOs and business groups, writing articles for publications aimed at general audiences (*Sanctuary, Earthkeeper, Connections*), and giving lectures. Last summer, PIE scientists Neill and Deegan led a hands-on field course for science writers, which was supported through the MBL Logan Science Journalist Program and PIE-PI Neill will continue to be involved in this project. “Adopt-a-Herring” (<http://www.ipswich-riverherring.com>), and “Adopt-a-Bass” programs and web pages directly engage the public in our research (Frank et al. 2009b). We bring our technical expertise to a growing number of NGOs and regulatory and management agencies including the Ipswich River Watershed Association, USFWS Parker River Wildlife Refuge, Great Marsh Habitat Restoration team, Massachusetts Coastal Zone management, and the Parker River Watershed Association. Responsibilities for maintaining these interactions are covered in our site management plan.

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SUPPLEMENTARY DOCUMENTS

DATA MANAGEMENT PLAN

Information Management

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 Ecosystem. This network provides researchers access to common information and data in addition to protected long-term storage. Data and information are also 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 the research.

Access by the public and scientific community to data and information has been provided since 1998 through the web site, <http://ecosystems.mbl.edu/pie>, but we are in the process of migrating to a new web site, <http://pie-lter.mbl.edu> (see below). To see our new structure and enhanced search capabilities, we suggest reviewers examine this site as well. The web site contains information on personnel, data, published and unpublished papers, reports and School Yard education. The data section features Core Research and Signature Data, Data Links, Education and Outreach and Physical Characteristics. PIE maintains an Intranet site with archived datasets from which the PIE web site is updated annually. Some datasets (streaming data logger data) are updated more frequently. The organization of the PIE home page mirrors the Intranet archive in nomenclature, which allows for easy updating of datasets. MBL researchers can directly access archived data on MBL's server. Non-MBL researchers have access to a secure FTP web site at MBL for archival back up of their data (both unprocessed and processed). 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 data (helpful when planning research schedules) are available on the Rowley field station website, <http://www.pielter.org/> and will be integrated in the new web site.

New PIE Web Site

In a collaborative effort with 8 other LTER sites (LNO, ARC, SEV, LUQ, NTL, VCR, JRN and NWT), we are migrating our web site to Drupal, an open source web based relational content management system. We made the decision to move to Drupal because management of the current PIE web site requires time-consuming manual editing of HTML for updating content, and the web site does not allow for search and discovery of information content. The development of this web site began in 2010 and is expected to be completed by 2013. A Drupal system uses a Linux or Windows OS and Apache, MySQL and PHP (LAMP or WAMP) installation. The resulting Drupal-based web site has powerful capabilities for data and information inquiry of a relational database via an Internet web interface. The Drupal Environmental Information Management System (DEIMS) collaborative, coordinated by Inigo San Gil (LNO, MCR), has grown to include more than LTER sites alone. The goal of PIE, collaborating LTER sites and other DEIMS sites is to provide a viable environmental information content management system with standardized core content types that will leverage programming/coding development. Sharing of code across sites is easily accomplished using Drupal modules and Drupal export/import capabilities of PHP code. Utilizing a variety of Drupal modules such as Views, Panels and Taxonomy (content tagging via controlled vocabulary) relational information content will be easily searched and discovered. The Drupal system, via open source shared modules, leverages the programming capabilities of thousands of

programmers around the world, <http://drupal.org/home>. The DEIMS collaborative has a repository of information located at <http://code.google.com/p/deims>.

PIE information and databases are stored on a MBL Microsoft Windows server with a level 3 RAID array that is backed up on an external drive nightly. Once a month the external drive is replaced and stored in an offsite location. The PIE Drupal web site is served via a Linux virtual machine, LAMP set up, which is backed up nightly and mirrored to an offsite location.

Data Management and Design of Research Projects

Data management and design of research projects is coordinated through an information management team. The information management team consists of: Anne Giblin (Lead PI), Joe Vallino (PI), Robert (Hap) Garritt (IM), Gil Pontius (PI) and research assistants associated with program areas. The team has the necessary leadership, knowledge and technical expertise for creating and maintaining the PIE research information. Hap Garritt, a senior research assistant 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. Hap has over 30 years experience in ecological research, an MS in Ecosystems Ecology and is very active in PIE research. Hap's regular research activities involve him 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. Past reviewers have commented that Hap's part time status as IM may not be sufficient. For the remainder of PIE III, Hap will work full time on information management and streaming telemetry data issues.

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.

Contributions of Data to Database

Individual researchers are responsible for providing metadata and data via an 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://www.lternet.edu/data/netpolicy.html>. Researchers using the facilities of the PIE LTER are expected to comply with the LTER policy 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 allows for consistent metadata entry and 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. Individual researchers are responsible for quality assurance, quality control, data entry, validation and analysis for their respective projects. 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. LTER researchers who fall behind in their data submission are referred to the Executive Committee for further action.

Data Accessibility and Timelines

Researchers on 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 realization for timely submittal of data sets for incorporation into the PIE

LTER database. Data are typically posted on the PIE web site within one to two years and selected data are made available in near real time to promote ecological awareness of the local environment. PIE follows the data release policy for the LTER network that states:

“There are two types of data: Type I (data that is 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)).”

More than 200 PIE datasets are easily accessible to PIE LTER scientists, local, regional, and state partners and the broader scientific community, Supplemental Table 8.4. Datasets are available across the broad breadth of PIE research in the watersheds and estuary. We currently have no registration requirements for either observing or downloading data from our web site, which has resulted in seamless access to all PIE LTER data. PIE data downloads on our web site 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. While our current system allows easy access to data, it does not allow us to track individual users using a registration interface. During 2012, we will begin integrating the Data Access Server interface developed by the LTER Network Office (LNO) with the new PIE Drupal web site as a means of standardized registration and documentation on the use of PIE data sets. The Data Access Server will require users interested in downloading data to register and comply with the LTER Network Data Access Policy (<http://www.lternet.edu/data/netpolicy.html>).

On-line PIE LTER data set usage for Years 2009-2011 is represented in Table 8.2.1. Analysis of years 2009-2011 PIE web server logs of non-associated PIE LTER investigators and others indicate that outside use of our data has increased by nearly 50% over the last 3 years. Much of this use comes from agencies such as USGS. PIE also gets individual requests via email and phone for particular data sets. Large data sets (> 15 GB) such as LIDAR from 2005 and 2006 have also been requested and made available via FTP, DVD or external hard drive.

Network Participation

The PIE LTER program participates in the annual LTER Information Managers meetings, contributes to network level databases of ClimDB, HydroDB, Personnel, Bibliography, Site DB, LTER Data Portal (Metacat Data) and EcoTrends and has been involved with LTER Network EML workshops. Hap Garritt is a member of the Unit Dictionary, DEIMS, Governance and GIS working groups and a member of the LTER IM Executive Committee (2007-2010). PIE contributed samples and data to the Microbial Inventory Research Across Diverse Aquatic LTERs project (MIRADA) and participated in a MIRADA LTER post ASM workshop at MBL in Woods

PIE Web Logs of Hits on Data Sets by non-PIE LTER Investigators			
Month	2009	2010	2011
JAN	66		238
FEB	162	25	54
MAR	92	98	147
APR	19	55	55
MAY	48	238	102
JUN	46	24	78
JUL	34	46	283
AUG	26	51	24
SEPT	83	141	66
OCT	178	120	88
NOV	377	404	99
DEC	57	239	490
Annual Total	1188	1441	1724

Table 8.2.1. Monthly use of PIE LTER data sets during 2009 – 2011 summarized from analyses of the PIE Web server log files. Use is represented as the number of times a data set has been accessed (Hits)^a by investigators not associated directly with PIE LTER. ^aNon-browsing activity web hits have been excluded using filters for spiders, crawlers and domains not representing normal browsing activity.

Hole, MA, Spring 2010, which addressed metadata structure for genomic and associated environmental data. PIE researchers Wil Wollheim (PI) and Inke Forbrich (Post-Doc) participated in the SensorNIS workshop, Hubbard Brook, NH during October 2011, discussing capabilities and opportunities for sharing resources in managing a variety of streaming data from remote data logging sensor networks (weather station, water quality and eddy flux stations).

PIE LTER supplemental funding for Information Management in 2010 and 2011 has been targeted toward the collaborative LTER DEIMS effort. Ongoing efforts include migration of existing metadata to Drupal content types, development of Drupal modules for converting Drupal content to EML and incorporation of the LTER Controlled Vocabulary and Unit Dictionary into DEIMS. Hap attended DEIMS training workshops at LNO, Albuquerque, NM, in October 2010 and November 2011. PIE has targeted direct collaboration with Jim Laundre, ARC LTER information manager and Excel metadata template author, for converting Excel metadata content to Drupal content types and developing common query structures (Views in Drupal). Common sharable views and displays will leverage efforts made by collaborating LTER sites enabling a similar “look, feel and function” to their DEIMs web sites.

Improvements to Data Accessibility

Past reviewers had trouble accessing PIE data from the LNO, and with accessing certain data sets including microbial data and models. The PIE LTER network web address of <http://pie.lternet.edu> has been fixed at the LNO to resolve to the current PIE LTER home page, <http://ecosystems.mbl.edu/pie> and will resolve to the new PIE Drupal site when it is complete.

Microbial genomic information for PIE is provided via an information data set, http://ecosystems.mbl.edu/PIE/data/mic/microbial_genomics.htm. The microbial genomic information includes citations, sequence accession numbers and instructions for producing downloadable genbank- and fasta-formatted text files of the sequences. This is easily done with Batch-entrez, <http://www.ncbi.nlm.nih.gov/sites/batchentrez>, using a small text file containing a list of accession numbers.

Modeling information has been updated: <http://ecosystems.mbl.edu/pie/data/mod/MOD.htm>. Links are provided to PIE modeler Joe Vallino’s web site which includes detailed information on past and current modeling. Modeling information from Vallino’s web site will be incorporated into the new PIE Drupal site.

PIE has 220 on line EML compliant data sets available at the LTER Data Portal, <http://metacat.lternet.edu/das/lter/advancedsearch> and the PIE web site, <http://ecosystems.mbl.edu/pie/data>. To improve data availability through the LTER NIS (Network Information System) and future release of PASTA (Provenance Aware Synthesis Tracking System), we are updating data sets from EML 2.0.1 to EML 2.1.0 compliancy. We currently have 81 EML 2.1.0 data sets and will continue updating the remaining datasets during 2012-2013.

Priorities and timelines of PIE IM for the next funding cycle:

Complete implementation of the PIE Drupal web site involves the following:

- 2012 – Migrate existing Excel EML compliant metadata to Drupal content via an Excel to Drupal module that is being developed using IM supplement funding.
- 2012 – Continue collaborative development of Drupal to EML 2.1.0 module.
- 2012 – Update datasets using LTER Controlled Vocabulary for LTER and PIE keywords.

- 2012 – Develop search and query capabilities of content using Drupal Views, Panels and Taxonomy modules and LTER and PIE controlled keywords.
- 2012/2013 – Develop geo-referenced views of content using Drupal Gmap and Open Layers modules. Geo-referenced views of content will provide maps of research sites with pop-up windows displaying data available for the associated site.
- 2012/2013 – Incorporate LTER Unit Dictionary into the Drupal metadata editor to standardize unit selection in PIE Drupal web site.

MILESTONE – 2013 Fully functional PIE Drupal web site that provides easily searchable access to PIE data and metadata.

LTER NIS PASTA-ready EML

- 2012/2013 – With a fully functional PIE Drupal site metadata will be PASTA ready. Data and metadata quality will be evaluated in coordination with the EML Metrics working group and EML congruency checker. The goal is to ensure that the metadata for the data correspond to each other and will function properly in the LTER NIS. This will be done as a continuation of our current collaboration with ARC LTER, also based at the MBL, and coordinated with the LTER NIS.

MILESTONE – 2014 EML 2.1.0 metadata and data ready for the LTER NIS PASTA release.

Streaming Sensor Data

- 2012/2013 – PIE will evaluate SensorNIS strategies for managing streaming data based on participation in the 2012 SensorNIS workshop. In particular PIE is interested in using the GCE Data Toolbox for processing PIE streaming data (weather, water quality sonde, in situ sensors) and for harvesting online data from USGS, NOAA NOS and NCDC that would complement the existing PIE database.

MILESTONE – 2014 Publish high quality, near real time streaming data on PIE Drupal web site

GIS

- 2012-2016 and on. Collaborate with the LTER IM GIS working group for presentation of GIS on the web. Generate EML 2.1.0 metadata from existing FGDC compliant metadata. Collaborate with other LTER sites for working across GIS platforms of ESRI ARCGIS, Clark University IDRISI and UNH River Networks.

Post-Doctoral Mentoring Plan

Each post-doctoral scholar on the PIE-LTER is assigned a primary mentor from one of our research focus areas. It is the responsibility of that mentor to assure that the post-doc gets orientated within the PIE-LTER and makes rapid progress beginning their work. While the general area of research is outlined by our research objectives we give the post-doc considerable leeway in adapting the project to his/her own specific interests. The mentor also encourages the post-doc to complete publication of their thesis papers. It is also the mentor's responsibility to assure that the post-doc participates in an ethics training program run by the MBL for all post-docs. Finally, this mentor will also assure that the post-doc has access and training in any equipment that they need and that they have sufficient help to accomplish their goals. As the project goes forward the post-doc may also be assigned a secondary mentor to broaden their research experience and may spend time in the lab of one of the non-MBL researchers.

The post-doc will meet regularly with a broader group of PIE PIs and will be asked to give informal updates on their progress every 2-3 months. They will also give formal presentations at our annual PIE-LTER all scientists meeting and give an annual seminar to the staff of the Ecosystems Center at the MBL. Post-docs are given funds to attend at least one national or international meeting per year. It will be a top priority to help post-docs develop their presentation and writing skills, both essential as they move forward in their professional development toward environmental careers. We also encourage our post-doc to improve their communication skills to policy makers and the general public. The PIE-LTER has close connections with the Parker River National Wildlife Refuge, the Parker River Association, and other local NGOs. We encourage our post-docs to make presentations to these groups and also provide them opportunities to make presentations to the general public, and to have some interaction with our K-12 students by attending their annual symposium.

Post-docs will be encouraged to interact with the broader Woods Hole community. Woods Hole is a rich scientific environment for a beginning scientist, with a wealth of seminars and potential contacts and future colleagues at MBL, the Woods Hole Research Center, and the Woods Hole Oceanographic Institution. MBL also has several educational partnerships and programs in which the post-docs can gain teaching experience if they indicate interest in honing those skills. Specifically, we have a joint PhD program with Brown University, and guest-lecturing opportunities are often available in Brown undergraduate and graduate courses in the Ecology and Evolutionary Biology (EEB) and Geological Sciences departments. (Brown is a 1.5-hour drive from Woods Hole). Also, the Ecosystems Center sponsors the Semester in Environmental Sciences (SES), an immersive, full "semester-abroad" program for 15-20 college undergrads taught here in-house every fall. The highlight of the semester for students is their carrying out independent, multi-week projects with mentors from the MBL community, and post-docs who are interested may mentor these students.

MBL requires that all post-docs will work with their mentors on an annual evaluation of progress, and this defined exercise will provide a clear time and place for any concerns to be addressed, annual goals set, and special acknowledgement of achievements noted.

SITE MANAGEMENT

GOVERNANCE AND COORDINATION

Overall direction and management are provided by lead PI, Anne Giblin, and the executive committee. The executive committee consists of Giblin, and the leaders of our major program areas. The current program coordinators are: Wil Wollheim (UNH) who coordinates work in the watershed, Jim Morris (USC) who coordinates work on the marshes and marsh response to sea level rise, Chuck Hopkinson (U. Ga.) who coordinates the work on carbon cycling in the estuary and marsh, Linda Deegan (MBL) who coordinates the work on consumers throughout PIE, Joe Vallino (MBL) who oversees modeling and hydrodynamics, and Gil Pontius (Clark) who coordinates the work on land use/land cover changes, and social science.

The executive committee is consulted on all financial matters and supplements requests, collects information for annual and final reports from other members of their program area, and is used to facilitate transitions in leadership. Coordinators keep all members of the LTER informed about activities and findings in their program area. Each program area holds regular meeting that bring together PIs, students, post-docs and research assistants. Often these meeting involve several groups meeting together, either formally or informally at the field station.

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 make presentations. At our annual meeting we summarize the results of individual program areas, synthesize across disciplines, and plan the research program for the following year. Graduate students present thesis ideas and participate in the planning for the upcoming field season. We also encourage representatives of the other governmental agencies and NGOs working in the area and teachers working with our education program to attend and give presentations on their work.

Major research directions and strategic planning, are discussed with all of the PIs and senior personnel on the project and decisions are reached by consensus. For the past two years we have had near monthly video or conference call of all of the PIs and senior personnel, as well as key research assistants, to develop our new questions and research approaches. This approach proved very successful, and we expect to continue to hold several meetings each year this way to supplement our annual meeting.

ENCOURAGING NON-LTER SCIENTIST PARTICIPATION AND COORDINATION

The major way we have been able to broaden long-term participation in the project is by writing grants with other non-LTER investigators. Some who began working with us this way, such as Mather and Polsky, are now members of the LTER project. Scientific coordination is achieved through our annual meeting, and by interactions with other PIE investigators. Our program coordinators usually serve as the key points of contact for long-term projects.

We encourage non-LTER scientists and students to work at PIE and whenever possible assist them with access to the site, housing and computer facilities while at the site, and data and maps to help plan their research. We coordinate logistics such as housing and boats through our web site. Investigators coming for short periods of time usually contact Giblin who puts them in contact with the PI or RA most able to assist them. Buchsbaum has played a key role in helping scientists from other LTER sites find useful sites for comparative studies.

EDUCATION and OUTREACH

Elizabeth Duff, of Massachusetts Audubon, serves as our education coordinator, and is included in all discussions that involve education and outreach. Duff is responsible for our schoolyard program and carries out teacher training and recruits new teachers into the program. She also spearheads the Perennial Pepperweed eradication program, which is joint project with Mass Audubon and the Parker River Wildlife Refuge and involves hundreds of volunteers and partners including the Gulf of Maine Institute. She interacts with PIE scientists to produce courses such as the climate change courses and the striped bass curriculum previously described.

Giblin interacts with teachers at the Governor's Academy High School. Students make long-term measurements in the marshes as part of their studies and PIE posts this data on our web site. We also have a summer internship program for a few select HS students for the summer. Linda Deegan normally supervises these interns and this year Deegan and Martha Mather will work with a teacher and two students under the RET program.

Polsky and Pontius direct the undergraduate Clark University Human-Environment Regional Observatory (HERO) NSF REU Site program and supervise students doing their projects, nearly all of which are done in PIE watersheds. PIE funded REUs are supervised by individual mentors each summer and each student creates a poster or gives a presentation to the community as part of their project. Wollheim is also supervising UNH undergraduate students doing research at PIE. These students will present their work at the annual Undergraduate Research Conference (URC) held at UNH each spring. This URC is one of the largest university research conferences in the country.

Our outreach activities have expanded continually since PIE's inception. Robert Buchsbaum, officially heads up our outreach activities. He plays a major role coordinating with government agencies and NGOs in the area as part of his position at Mass Audubon. Buchsbaum is also actively involved in many aspects of higher trophic level and marsh research at PIE and takes the lead in bird research. He coordinates between PIE, the Parker River National Wildlife Refuge (PRNWR) and Mass Audubon to assemble regional bird data which is then posted on the PIE site. However, our interactions have grown to the point that most PIs now take an active role in outreach and in collaborating with local or regional partners. Giblin takes the lead in most interactions with PRNWR, which is where our eddy flux tower is located, with the Essex County Greenbelt, and with Mass Coastal Zone Management. She is also on the board of the Gulf of Maine Institute. Deegan and Mather coordinate with all groups interested in fisheries including sports fisherman's associations, local and state fisheries management agencies, and regional groups interested in striped bass and herring. Wollheim is our primary contact with both the Ipswich and Parker River watershed association and these organizations have participated in our sampling program as volunteers. In the coming year Deegan, Mather, and Wollheim will all work with the Department of Ecological Restoration coordinating research with planned dam and culvert removals. Hopkinson has been coordinating with local shell fishermen and shell fish regulatory agencies. Neill directs the science journalism program and is director of the joint Brown MBL program. Morris coordinates with regional science and management groups interested in coastal sea level rise. Vallino coordinates PIE hydrodynamic modeling efforts with other regional 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 been able to increase the number of minority students participating in the program by adding the Collins Middle School in Salem, MA to our program. 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 Brown and the MBL-SES program, which have active minority recruiting programs. The addition of Jen Bowen, UMass Boston (UMB), should also increase our minority applicants. UMB serves the largest minority population (44% following federal definitions) of any public research university in New England, and fully 48% of UMBs undergraduates were first in their families to attend college. At the graduate and post-graduate level, the PIs at each of our institutions use list serves set up by scientific societies and their own HR department to assure a wide distribution of position announcements to venues including the annual conference for the Society for Advancing Chicano/Latino and Native Americans in Science (SACNAS) and through minority recruiting efforts of professional societies of PIs (e.g., AFS, ESA, ASLO, ASCE).

PI ADDITIONS

We are bringing in 4 early-mid career scientists as senior personnel who we believe will be capable of taking on leadership roles in PIE IV. All of these scientists are currently working at PIE with outside funding and we assist them with housing and access to the field sites. Peter Raymond (Yale) is

collaborating with us making measurements of carbon fluxes in tidal creeks. Pete has a long association with PIE and was a post-doc on the project when it first started. Nat Weston (Villanova) is working with Chuck Hopkinson on whole system metabolism in the estuary. Nat is a biogeochemist who also has a long association with PIE and did his thesis at GCE. Sergio Fagherazzi (BU) is a geomorphologist who began working at PIE several years ago. Fagherazzi also has research projects at the VCR-LTER and is making comparative measurements between PIE and VCR. Jennifer Bowen (U. Mass Boston) brings microbial expertise to PIE and is currently collaborating with Linda Deegan on the TIDE experiments. All of these scientists bring new strengths to PIE and are at a stage in their career where they will soon be able to take on a greater leadership role. We are also adding David Johnson, who has worked at PIE for both his Ph.D. and post-doctoral work, as senior personnel. David is now a Research Associate at MBL. In addition to bringing his expertise in invertebrates to the research at PIE, David has taken on a large role in mentoring undergraduates and interns.

PI and LEADERSHIP TRANSITIONS

A number of PIE PIs will end their involvement either at the end of PIE III or sometime during PIE IV. Based upon the experience of other sites we believe that a 2-3 year period of transition, with overlap, is optimum 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. By the time of our 3 year review next year we expect to determine which PIs will stay on for a least part of PIE IV and which will not and begin planning appropriately.

ADVISORY GROUPS

PIE did not have a permanent standing advisory board. Last year we convened an outside group of advisors to examine our overall program. This was extremely valuable and we will continue to obtain regular outside perspectives on our research programs. For the remainder of PIE III we will set up an advisory group, but rotate some of the members each year to target advice in specific program areas.

FIELD FACILITIES

In 2003 the MBL purchased the Marshview Farm in Newbury, MA, which greatly expanded our facilities. This property has sleeping space for 13, a small lab, and substantial storage space for equipment and supplies. The Marshview facility is supplemented by the Rowley Field House, which is rented from a local land trust, the Essex County Greenbelt Association. The Rowley House sleeps up to 8 in tight dorm-type accommodations. Most importantly it provides on-site dock facilities for 3 boats to give us easy and immediate access to the water. The Rowley site also provides walking access to many of our field sites. These two facilities have been sufficient for direct LTER needs over the last 7 years and most of the time we have been able to also accommodate students, PIs, and post-docs from related projects. However, there are times when requests exceed our capacity.

During PIE II we received NSF funds for a planning grant to upgrade the Marshview Farmhouse and barn so it would better serve PIE's needs. Since that plan was developed, the nearby Parker River Wildlife Refuge built a large auditorium and is pleased to have us use it, alleviating the need for this type of space on site. As a result, we have revised the plans for the site and while reducing its scope, developed a plan that should meet PIE's needs over the next several decades. Our goal is to modernize the house, increase sleeping capacity, and expand our laboratory space. Because of concerns in the watershed over energy and water issues we plan for a very efficient "green" building with innovative sewage treatment.

While these major changes require outside funding, over the last two years we have made a number of small upgrades to the building including improving the water. We have taken down the poorly built addition to the barn in anticipation of replacing it with a new addition that would serve as a field lab. During this cycle we will pursue funding to begin to renovate the building and have the support of the MBL development office to pursue private funds for this purpose. We instituted a very small fee to outside projects to help maintain and support the facilities and docks.

SUPPLEMENTARY DOCUMENTS

Table 8.4 Electronically Available Data

Data sets available on PIE LTER web site, <http://ecosystems.mbl.edu/pie/data/datacatalog.htm>, as of 3/1/2012.

Data available by LTER core areas: 1) Primary production, 2) Organic matter, 3) Nutrients, 4) Disturbance, 5) Dynamics of populations.

Dataset	Dataset Title	Lead PI	Begin Year	End Year	LTER Core Area
WATERSHEDS					
WAT-VA-Inputs	Water chemistry of the Ipswich & Parker Rivers	Wollheim	1993	2010	2, 3
WAT-VA-Load	Annual nutrient loading and yield to Plum Island Estuary	Wollheim	1993	2010	2, 3
WAT-VA-SigmaNutrients	Daily nutrients from Sigma auto samplers in various watershed locations	Wollheim	2001	2009	2, 3, 4
WAT-YSI-SIGMA-timeseries	Nutrient grab samples from 6 sites of the Ipswich and Parker Rivers	Wollheim	2001	2009	2, 3, 4
WAT-PR-ParkerDischarge01101000	Parker River daily discharge @ Byfield, MA	Wollheim	1945	2011	4
WAT-IP-IpswichDischarge01102000	Ipswich River daily discharge near Ipswich, MA	Wollheim	1930	2011	4
WAT-IP-IpswichDischarge01101500	Ipswich River daily discharge near S. Middleton, MA	Wollheim	1938	2011	4
WAT-VA-StreamNutrient	Rain event nutrient time course for 8 streams	Hopkinson	1992	1993	3, 4
WAT-IP-Catchments	Nutrients of Ipswich River, 1st to 4th order catchments	Hopkinson	1999	2000	3
WAT-MBL-IP-catchments	Nutrients of Ipswich River, 1st to 4th order catchments, to standardize IDs	Hopkinson	2000	2002	3
WAT-UNH-IP-catchments	Nutrient data set of Ipswich River headwaters with help from Ipswich River Watershed Association.	Wollheim	2001	2002	3
WAT-UNH-PR-catchments	Nutrient data set of Parker River headwaters with help from Parker River Cleanwater Watershed Association.	Wollheim	2001	2002	3
WAT-IP-1998Monthly	Nutrients of Ipswich River main stem, major tributaries	Hopkinson	1998	1999	3
WAT-IP-MonthlySampling	Nutrients of Ipswich River main stem, major tributaries	Hopkinson	1999	2001	3
WAT-VA-rainfall	Wet deposition solutes for Ipswich River basin	Hopkinson	2000	2001	3
WAT-YSI-FishBR-2001	Year 2001 YSI continuous water quality data, Fish Brook, Middleton, MA	Wollheim	2001	2001	4
WAT-YSI-FishBR-2002	Year 2002 YSI continuous water quality data, Fish Brook, Middleton, MA	Wollheim	2002	2002	4
WAT-YSI-Forest-2001	Year 2001 YSI continuous water quality data, Cart Creek, Newbury, MA	Wollheim	2001	2001	4
WAT-YSI-Forest-2002	Year 2002 YSI continuous water quality data, Cart Creek, Newbury, MA	Wollheim	2002	2002	4
WAT-YSI-Forest-2003	Year 2003 YSI continuous water quality data, Cart Creek, Newbury, MA	Wollheim	2003	2003	4
WAT-YSI-Forest-2004	Year 2004 YSI continuous water quality data, Cart Creek, Newbury, MA	Wollheim	2004	2004	4

Dataset	Dataset Title	Lead PI	Begin Year	End Year	LTER Core Area
WAT-YSI-Forest-2005	Year 2005 YSI continuous water quality data, Cart Creek, Newbury, MA	Wollheim	2005	2005	4
WAT-YSI-Forest-2006	Year 2006 YSI continuous water quality data, Cart Creek, Newbury, MA	Wollheim	2006	2006	4
WAT-YSI-Forest-2007	Year 2007 YSI continuous water quality data, Cart Creek, Newbury, MA	Wollheim	2007	2007	4
WAT-YSI-Forest-2008	Year 2008 YSI continuous water quality data, Cart Creek, Newbury, MA	Wollheim	2008	2008	4
WAT-YSI-Forest-2009	Year 2009 YSI continuous water quality data, Cart Creek, Newbury, MA	Wollheim	2009	2009	4
WAT-YSI-UpperIps-2001	Year 2001 YSI continuous water quality data, Ipswich River, North Reading, MA	Wollheim	2001	2001	4
WAT-YSI-UpperIps-2002	Year 2002 YSI continuous water quality data, Ipswich River, North Reading, MA	Wollheim	2002	2002	4
WAT-YSI-UpperIps-2003	Year 2003 YSI continuous water quality data, Ipswich River, North Reading, MA	Wollheim	2003	2003	4
WAT-YSI-Urban-2001	Year 2001 YSI continuous water quality data, Saw Mill Brook, Burlington, MA	Wollheim	2001	2001	4
WAT-YSI-Urban-2002	Year 2002 YSI continuous water quality data, Saw Mill Brook, Burlington, MA	Wollheim	2002	2002	4
WAT-YSI-Urban-2003	Year 2003 YSI continuous water quality data, Saw Mill Brook, Burlington, MA	Wollheim	2003	2003	4
WAT-YSI-Urban-2004	Year 2004 YSI continuous water quality data, Saw Mill Brook, Burlington, MA	Wollheim	2004	2004	4
WAT-YSI-Urban-2005	Year 2005 YSI continuous water quality data, Saw Mill Brook, Burlington, MA	Wollheim	2005	2005	4
WAT-YSI-Urban-2006	Year 2006 YSI continuous water quality data, Saw Mill Brook, Burlington, MA	Wollheim	2006	2006	4
WAT-YSI-Urban-2007	Year 2007 YSI continuous water quality data, Saw Mill Brook, Burlington, MA	Wollheim	2007	2007	4
WAT-YSI-Urban-2008	Year 2008 YSI continuous water quality data, Saw Mill Brook, Burlington, MA	Wollheim	2008	2008	4
WAT-YSI-Urban-2009	Year 2009 YSI continuous water quality data, Saw Mill Brook, Burlington, MA	Wollheim	2009	2009	4
WAT-YSI-Swamp-2005	Year 2005 YSI continuous water quality data, Cedar Swamp, Bear Brook, Reading, MA	Wollheim	2005	2005	4
WAT-YSI-Swamp-2006	Year 2006 YSI continuous water quality data, Cedar Swamp, Bear Brook, Reading, MA	Wollheim	2006	2006	4
WAT-YSI-Swamp-2007	Year 2007 YSI continuous water quality data, Cedar Swamp, Bear Brook, Reading, MA	Wollheim	2007	2007	4
WAT-YSI-Swamp-2008	Year 2008 YSI continuous water quality data, Cedar Swamp, Bear Brook, Reading, MA	Wollheim	2008	2008	4
WAT-YSI-Swamp-2009	Year 2009 YSI continuous water quality data, Cedar Swamp, Bear Brook, Reading, MA	Wollheim	2009	2009	4
MARSH					
MAR-RO-Transects	Marsh vegetation along 5 transects on the Rowley River	Hopkinson	1998	1998	1, 2, 3
MAR-RO-Sedimentation	Sedimentation along five transects on the Rowley River	Hopkinson	1998	1998	2

Dataset	Dataset Title	Lead PI	Begin Year	End Year	LTER Core Area
MAR-RO-Marker-Horizon	Marsh sediment marker horizon data from Rowley marshes	Giblin	2000	2011	2, 4
MAR-RO-SET	Marsh platform SET data from Rowley marshes	Giblin	2002	2011	2, 4
MAR-PR-Porewater	Porewater nutrients, Parker River, MA	Giblin	2004	2010	2, 3
MAR-VA-Porewater	Porewater nutrients (Rowley, Parker Rivers, MA) (Wells, ME)	Morris	1998	2000	3, 4
MAR-PR-Wtable-RRA-2001	Water table heights at the railroad Spartina marsh on Parker River	Hopkinson	2001	2001	4
MAR-PR-Wtable-RRB-2001	Water table heights at the railroad Spartina marsh on Parker River	Hopkinson	2001	2001	4
MAR-PR-Wtable-RRA-2002	Water table heights at the railroad Spartina marsh on Parker River	Hopkinson	2002	2002	4
MAR-PR-Wtable-RRB-2002	Water table heights at the railroad Spartina marsh on Parker River	Hopkinson	2002	2002	4
MAR-PR-Wtable-RR-2003	Water table heights at the railroad Spartina marsh on Parker River	Hopkinson	2003	2003	4
MAR-PR-Wtable-RR-2004	Water table heights at the railroad Spartina marsh on Parker River	Hopkinson	2004	2004	4
MAR-PR-Wtable-RR-2006	Water table heights at the railroad Spartina marsh on Parker River	Hopkinson	2006	2006	4
MAR-PR-Wtable-RR-2007	Water table heights at the railroad Spartina marsh on Parker River	Hopkinson	2007	2007	4
MAR-PR-Wtable-RR-Apr2008	Water table heights at the railroad Spartina marsh on Parker River, Apr-Oct 2008	Giblin	2008	2008	4
MAR-PR-Wtable-RR-Oct2008	Water table heights at the railroad Spartina marsh on Parker River, Oct-Dec 2008	Giblin	2008	2008	4
MAR-PR-Wtable-RR-2009	Water table heights at the railroad Spartina marsh on Parker River	Giblin	2009	2009	4
MAR-PR-Wtable-RR-Apr2010	Water table heights at the railroad Spartina marsh on Parker River, Apr-Sep 2010	Giblin	2010	2010	4
MAR-PR-Wtable-RR-Oct2010	Water table heights at the railroad Spartina marsh on Parker River, Oct-Nov 2010	Giblin	2010	2010	4
MAR-PR-Wtable-RR-Mar2011	Water table heights at the railroad Spartina marsh on Parker River, Mar-Sep 2011	Giblin	2011	2011	4
MAR-PR-Wtable-RR-Sep2011	Water table heights at the railroad Spartina marsh on Parker River, Sep-Nov 2011	Giblin	2011	2011	4
MAR-PR-Wtable-TA-2001	Water table heights in Typha marsh on the Parker River	Hopkinson	2001	2001	4
MAR-PR-Wtable-TB-2001	Water table heights in Typha marsh on the Parker River	Hopkinson	2001	2001	4
MAR-PR-Wtable-TA-2002	Water table heights in Typha marsh on the Parker River	Hopkinson	2002	2002	4
MAR-PR-Wtable-TB-2002	Water table heights in Typha marsh on the Parker River	Hopkinson	2002	2002	4
MAR-PR-Wtable-T-2003	Water table heights in Typha marsh on the Parker River	Hopkinson	2003	2003	4
MAR-PR-Wtable-T-2004	Water table heights in Typha marsh on the Parker River	Hopkinson	2004	2004	4
MAR-PR-Wtable-T-2006	Water table heights in Typha marsh on the Parker River	Hopkinson	2006	2006	4
MAR-PR-Wtable-T-2007	Water table heights in Typha marsh on the Parker River	Hopkinson	2007	2007	4

Dataset	Dataset Title	Lead PI	Begin Year	End Year	LTER Core Area
MAR-PR-Wtable-T-Apr2008	Water table heights in Typha marsh on the Parker River, Apr-Oct 2008	Giblin	2008	2008	4
MAR-PR-Wtable-T-Oct2008	Water table heights in Typha marsh on the Parker River, Oct-Dec 2008	Giblin	2008	2008	4
MAR-PR-Wtable-T-2009	Water table heights in Typha marsh on the Parker River	Giblin	2009	2009	4
MAR-PR-Wtable-T-2010	Water table heights in Typha marsh on the Parker River	Giblin	2010	2010	4
MAR-PR-Wtable-T-Mar2011	Water table heights in Typha marsh on the Parker River, Mar-Sep 2011	Giblin	2011	2011	4
MAR-PR-Wtable-T-Sep2011	Water table heights in Typha marsh on the Parker River, Sep-Nov 2011	Giblin	2011	2011	4
LTE-MP-LAC-biomassmeans	Biomass, <i>Spartina alterniflora</i> , aboveground, Law's Point, Rowley River, MA	Morris	1999	2011	1
LTE-MP-LPC-biomassmeans	Biomass, <i>Spartina patens</i> , aboveground, Law's Point, Rowley River, MA	Morris	2001	2011	1
LTE-MP-NAC-biomassmeans	Biomass, <i>Spartina alterniflora</i> , aboveground, Goat Island, North Inlet, SC	Morris	1984	2011	1
LTE-MP-LAC-productivitymeans	Annual productivity, <i>Spartina alterniflora</i> , Law's Point, Rowley River, MA	Morris	1999	2011	1
LTE-MP-LPC-productivitymeans	Annual productivity, <i>Spartina patens</i> , Law's Point, Rowley River, MA	Morris	2001	2011	1
LTE-MP-NAC-productivitymeans	Annual productivity, <i>Spartina alterniflora</i> , Goat Island, North Inlet, SC	Morris	1984	2011	1
LTE-MP-LAC-porewatermeans	Nutrient concentrations from porewater, <i>Spartina alterniflora</i> dominated marsh, Law's Point, Rowley River, MA	Morris	1999	2011	3
LTE-MP-LPC-porewatermeans	Nutrient concentrations from porewater, <i>Spartina patens</i> dominated marsh, Law's Point, Rowley River, MA	Morris	2000	2011	3
LTE-MP-OTC-porewatermeans	Nutrient concentrations from porewater, <i>Typha</i> sp. dominated marsh, Upper Parker River, Newbury, MA	Morris	2000	2011	3
LTE-MP-NAC-porewatermeans	Nutrient concentrations from porewater, <i>Spartina alterniflora</i> dominated marsh, Goat Island, North Inlet, SC	Morris	1994	2011	3
LTE-MP-LAC-elevationmeans	Marsh surface elevation, <i>Spartina alterniflora</i> dominated marsh, Law's Point, Rowley River, MA	Morris	1999	2011	2, 4
LTE-MP-LPC-elevationmeans	Marsh surface elevation, <i>Spartina patens</i> dominated marsh, Law's Point, Rowley River, MA	Morris	2000	2011	2, 4
LTE-MP-NAC-elevationmeans	Marsh surface elevation, <i>Spartina alterniflora</i> dominated marsh, Goat Island, North Inlet, SC	Morris	1996	2011	2, 4
WATER COLUMN					
EST-PR-O2	Parker River Plum Island Sound, dawn & dusk metabolism transects	Hopkinson	1995	2010	1, 2, 4
EST-PR-O2info	Information data file for oxygen dawn & dusk metabolism transect file EST-PR-O2	Hopkinson	1995	2000	1, 2, 4
EST-PR-NUT	Parker River Plum Island Sound, water chemistry transects	Hopkinson	1994	2010	1, 2, 3, 4

Dataset	Dataset Title	Lead PI	Begin Year	End Year	LTER Core Area
EST-PR-ChemTax	Phytoplankton identification using HPLC and Chem Taxonomy, Plum Island Estuary	Hopkinson	2003	2009	5
MON-PR-MBYSI2000	Year 2000 YSI continuous water quality data, Parker River, Middle Rd.	Hopkinson	2000	2000	1, 2, 4
MON-PR-MBYSI2001	Year 2001 YSI continuous water quality data, Parker River, Middle Rd.	Hopkinson	2001	2001	1, 2, 4
MON-PR-MBYSI2002	Year 2002 YSI continuous water quality data, Parker River, Middle Rd.	Hopkinson	2002	2002	1, 2, 4
MON-PR-MBYSI2003	Year 2003 YSI continuous water quality data, Parker River, Middle Rd.	Hopkinson	2003	2003	1, 2, 4
MON-PR-MBYSI2004	Year 2004 YSI continuous water quality data, Parker River, Middle Rd.	Hopkinson	2004	2004	1, 2, 4
MON-PR-MBYSI2005	Year 2005 YSI continuous water quality data, Parker River, Middle Rd.	Hopkinson	2005	2005	1, 2, 4
MON-PR-MBYSI2006	Year 2006 YSI continuous water quality data, Parker River, Middle Rd.	Hopkinson	2006	2006	1, 2, 4
MON-PR-MBYSI2007	Year 2007 YSI continuous water quality data, Parker River, Middle Rd.	Hopkinson	2007	2007	1, 2, 4
MON-PR-MBYSI2008	Year 2008 YSI continuous water quality data, Parker River, Middle Rd.	Hopkinson	2008	2008	1, 2, 4
MON-PR-MBYSI2009	Year 2009 YSI continuous water quality data, Parker River, Middle Rd.	Hopkinson	2009	2009	1, 2, 4
MON-PR-RT1AYSI2000	Year 2000 YSI continuous water quality data, Parker River, Rt1A	Hopkinson	2000	2000	1, 2, 4
MON-PR-RT1AYSI2001	Year 2001 YSI continuous water quality data, Parker River, Rt1A	Hopkinson	2001	2001	1, 2, 4
MON-PR-RT1AYSI2002	Year 2002 YSI continuous water quality data, Parker River, Rt1A	Hopkinson	2002	2002	1, 2, 4
MON-SO-IBYCYSI2000	Year 2000 YSI continuous water quality data, Plum Island Sound, IBYC	Hopkinson	2000	2000	1, 2, 4
MON-SO-IBYCYSI2001	Year 2001 YSI continuous water quality data, Plum Island Sound, IBYC	Hopkinson	2001	2001	1, 2, 4
MON-SO-IBYCYSI2002	Year 2002 YSI continuous water quality data, Plum Island Sound, IBYC	Hopkinson	2002	2002	1, 2, 4
MON-SO-IBYCYSI2003	Year 2003 YSI continuous water quality data, Plum Island Sound, IBYC	Hopkinson	2003	2003	1, 2, 4
MON-SO-IBYCYSI2004	Year 2004 YSI continuous water quality data, Plum Island Sound, IBYC	Hopkinson	2004	2004	1, 2, 4
MON-SO-IBYCYSI2005	Year 2005 YSI continuous water quality data, Plum Island Sound, IBYC	Hopkinson	2005	2005	1, 2, 4
MON-SO-IBYCYSI2006	Year 2006 YSI continuous water quality data, Plum Island Sound, IBYC	Hopkinson	2006	2006	1, 2, 4
MON-SO-IBYCYSI2007	Year 2007 YSI continuous water quality data, Plum Island Sound, IBYC	Hopkinson	2007	2007	1, 2, 4
MON-SO-IBYCYSI2008	Year 2008 YSI continuous water quality data, Plum Island Sound, IBYC	Hopkinson	2008	2008	1, 2, 4
MON-SO-IBYCYSI2009	Year 2009 YSI continuous water quality data, Plum Island Sound, IBYC	Hopkinson	2009	2009	1, 2, 4
MON-SO-IBYCYSI2010	Year 2010 YSI continuous water quality data, Plum Island Sound, IBYC	Hopkinson	2010	2010	1, 2, 4
BENTHOS					
BEN-PR-Flux	Benthic metabolism and nutrient cycling in Parker & Rowley Rivers	Giblin	1993	2009	3, 4

Dataset	Dataset Title	Lead PI	Begin Year	End Year	LTER Core Area
BEN-PR-Sediment	Benthic sediment porewater chemistry in Parker & Rowley Rivers	Giblin	1993	2010	2, 3
HIGHER TROPIC LEVELS					
HTL-PIE-YearlyIsotopeSurvey	Annual stable isotope functional group surveys	Deegan	1999	2008	2, 3, 5
HTL-PIE-Survey-1993	Monthly aquatic macrofauna sampling during 1993	Deegan	1993	1993	5
HTL-PIE-Survey-1994	Monthly aquatic macrofauna sampling during 1994	Deegan	1994	1994	5
HTL-PIE-Survey-1997	Monthly aquatic macrofauna sampling during 1997	Deegan	1997	1997	5
HTL-PIE-Survey-1998	Monthly aquatic macrofauna sampling during 1998	Deegan	1998	1998	5
HTL-PIE-Survey-1999	Monthly aquatic macrofauna sampling during 1999	Deegan	1999	1999	5
HTL-PIE-Survey-2002	Monthly aquatic macrofauna sampling during 2002	Deegan	2002	2002	5
HTL-PR-Isotope	Stable isotope survey of aquatic macrofauna in Plum Island Estuary	Deegan	1993	1994	2, 3, 5
HTL-SO-Bird	Decade average counts for selected birds in Plum Island Sound	Buchsbaum	1930	1999	5
HTL-MAR-BreedingBirds	Surveys of salt marsh breeding birds using point counts	Buchsbaum	2004	2011	5
MON-EX-PRNWR-Breeding-Birds	Breeding bird census data at the Parker River National Wildlife Refuge	Buchsbaum	1994	2002	5
MON-EX-PRNWR-Salt-Marsh-Birds	Salt marsh bird census data at the Parker River National Wildlife Refuge	Buchsbaum	2001	2009	5
MON-EX-PRNWR-Volunteer-Birds	Bird observations by volunteers at the Parker River National Wildlife Refuge	Buchsbaum	1994	2003	5
LTE-TIDE-NektonFlumeDensity	Nekton species counts and density from flume net collections along Rowley River tidal creeks	Deegan	2003	2011	3, 4, 5
LTE-TIDE-NektonFlumeIndividual	Nekton individual data from flume net collections along Rowley River tidal creeks	Deegan	2003	2011	3, 4, 5
LTE-TIDE-Macroinfauna	Macroinfauna counts from marsh cores along Rowley River tidal creeks	Johnson	2003	2006	3, 4, 5
LTE-TIDE-MelampusIndividBiomass	Melampus bidentatus (coffee bean snail) length and biomass measurements along Rowley River tidal creeks	Johnson	2009	2010	3, 4, 5
LONG TERM EXPERIMENTS					
LTE-MP-SET-means	Summarized sediment elevation table data from marsh fertilized plots	Morris	1999	2011	2, 3, 4
LTE-MP-SET-raw	Raw sediment elevation table data from marsh fertilized plots	Morris	1999	2011	2, 3, 4
LTE-MP-NIN-SET-means	Marsh surface elevation data at a <i>Spartina alterniflora</i> -dominated salt marsh at Goat Island, North Inlet, Georgetown, SC.	Morris	1996	2011	2, 3, 4
LTE-MP-LPP-biomass	Vegetation biomass from <i>Spartina patens</i> marsh fertilized plots	Morris	2000	2011	1, 3, 4
LTE-MP-LPA-biomass	Vegetation biomass from <i>Spartina alterniflora</i> marsh fertilized plots	Morris	1999	2011	1, 3, 4

Dataset	Dataset Title	Lead PI	Begin Year	End Year	LTER Core Area
LTE-MP-ORT-biomass	Biomass measurements of <i>Typha</i> sp. at Upper Parker River brackish marsh site.	Morris	2002	2008	1, 3
LTE-MP-NIN-biomass	Aboveground biomass data from a <i>Spartina alterniflora</i> -dominated salt marsh plots in North Inlet, Georgetown, SC.	Morris	1984	2011	1, 3, 4
LTE-MP-LPA-productivity	Annual productivity at <i>Spartina alterniflora</i> -dominated salt marsh plots at Law's Point, Rowley, MA	Morris	1999	2011	1, 3, 4
LTE-MP-NIN-productivity	Annual productivity at <i>Spartina alterniflora</i> -dominated salt marsh plots in North Inlet, Georgetown, SC.	Morris	1985	2011	1, 3, 4
LTE-MP-porewater	Nutrient concentrations from porewater samples at three marsh fertilization experimental research sites in the low marsh (<i>Spartina alterniflora</i> dominated) and high marsh (<i>Spartina patens</i> dominated) at Law's Point and on the upper Parker River (<i>Typha</i> sp. dominated marsh).	Morris	1999	2011	3
LTE-MP-NIN-porewater	Nutrient concentrations from porewater samples at <i>Spartina alterniflora</i> -dominated salt marsh plots in North Inlet, Georgetown, SC.	Morris	1993	2011	3
LTE-TC-NUT	Pre-fertilization water-column nutrients in tidal creeks	Deegan	1998	2001	1, 2, 3
LTE-TC-BenChl	Pre-fertilization benthic chlorophyll concentration in tidal creeks	Deegan	1998	2002	1, 2
LTE-TIDE-BenChla	Benthic algae chlorophyll measurements along Rowley River tidal creeks associated with long term fertilization experiments.	Deegan	2003	2009	1, 2, 3, 4
LTE-TIDE-MarshPlantStemCount	Marsh plant species stem counts along Rowley River tidal creeks associated with long term fertilization experiments.	Deegan	2003	2011	1, 3, 4
LTE-TIDE-MarshPlantShootStats	Marsh plant species shoot height, weight and diameters along Rowley River tidal creeks associated with long term fertilization experiments.	Deegan	2004	2011	1, 3, 4
LTE-TIDE-MarshPlantFreq	Marsh plant species frequency of occurrence along Rowley River tidal creeks associated with long term fertilization experiments.	Deegan	2004	2011	1, 3, 4, 5
LTE-TIDE-MarshPlantCHN	Marsh plant species stem C:H:N data for Rowley River tidal creeks associated with long term fertilization experiments.	Deegan	2004	2011	1, 2, 3, 4
LTE-TIDE-MarshPlantCover	Marsh plant species percent cover along Rowley River tidal creeks associated with long term fertilization experiments.	Deegan	2004	2011	1, 3, 4, 5
LTE-TIDE-LENS-2009-geotech	2009 LENS geotechnical core results	Deegan	2009	2009	2
LTE-TIDE-LENS-2009-above-bio	2009 LENS aboveground biomass	Deegan	2009	2009	1, 2
LTE-TIDE-LENS-2009-below-bio	2009 LENS belowground biomass	Deegan	2009	2009	1, 2
LTE-TC-GreenwoodIsotopes	Stable isotopes of organisms in Greenwood Creek	Deegan	2001	2001	1, 2, 3, 4, 5
LTE-MD-VEGSTN	Physical layout of sites in hayed and reference areas	Buchsbaum	2000	2000	1, 2, 4, 5

Dataset	Dataset Title	Lead PI	Begin Year	End Year	LTER Core Area
LTE-MD-VEGTRANS	Plant species presence in hayed and control areas	Buchsbaum	2000	2010	1, 2, 4, 5
LTE-MD-VEGQUADS	Vegetation cover in hayed and control areas	Buchsbaum	2000	2010	1, 2, 4, 5
LTE-MD-EARLYVEG	Vegetation biomass & shoot densities at hayed and reference sites	Buchsbaum	2000	2000	1, 2, 4, 5
LTE-MD-EOYBIOMASS	Vegetation biomass & cover, end of season at hayed and reference sites	Buchsbaum	2000	2001	1, 2, 4, 5
LTE-MD-BIRD-HAY-STN	List of stations used for bird counts in hayed and reference sites	Buchsbaum	2000	2000	1, 2, 4, 5
LTE-MD-BIRD-HAY-DATA	Bird observations in newly hayed and adjacent reference sites	Buchsbaum	2000	2001	1, 2, 4, 5
LTE-MF-GREENWOOD-CLUBHEAD-VEGST	Vegetation transect physical layout at the enriched and reference sites	Buchsbaum	2002	2002	1, 3, 4, 5
LTE-MF-GREENWOOD-CLUBHEAD-VEGQD	Plant species percent cover at enriched and reference sites	Buchsbaum	2002	2002	1, 3, 4, 5
LTE-MF-GREENWOOD-CLUBHEAD-EOY-BM	Vegetation biomass & cover, end of season at enriched and reference sites	Buchsbaum	2002	2002	1, 3, 4, 5
LTE-MF-GREENWOOD-CLUBHEAD-VEGTR	Vegetation presence or absence at enriched and reference sites	Buchsbaum	2002	2002	1, 3, 4, 5
LTE-EX-ARGILLA-RM-VEGSTN	Vegetation transect physical layout on Argilla Rd and Rough Meadows	Buchsbaum	1995	2002	1, 4, 5
LTE-EX-ARGILLA-RM-VEGQUADS	Plant species percent cover at Argilla Rd and Rough Meadows marshes	Buchsbaum	1999	2002	1, 4, 5
LTE-EX-ARGILLA-RM-VEGTRANS	Plant species presence in Argilla Rd and Rough Meadows marsh	Buchsbaum	1995	2002	1, 4, 5
LTE-EX-ARGILLA-RM-PHRAGHEIGHTS	Phragmites heights at Argilla Rd and Rough Meadows marshes	Buchsbaum	1997	2002	1, 4, 5
SHORT TERM PROJECTS					
STP-PR-Mesocosm	Mesocosm experiment testing quality & quantity of DOM on food webs, 1994	Hopkinson	1994	1994	1, 2, 3, 4, 5
PHY-PR-SF6-1996	SF6 addition concentration gradients and wind speed in Parker River	Hopkinson	1996	1996	
SCHOOLYARD					
MON-PR-GDATrans1Middle2000	GDA Parker River Middle Rd. vegetation transect #1 during year 2000	Buchsbaum	2000	2000	5
MON-PR-GDATrans2Middle2000	GDA Parker River Middle Rd. vegetation transect #2 during year 2000	Buchsbaum	2000	2000	5
MON-PR-GDATrans3Middle2000	GDA Parker River Middle Rd. vegetation transect #3 during year 2000	Buchsbaum	2000	2000	5
MON-PR-GDATrans4Middle2000	GDA Parker River Middle Rd. vegetation transect #4 during year 2000	Buchsbaum	2000	2000	5
MON-PR-GDATrans5Middle2000	GDA Parker River Middle Rd. vegetation transect #5 during year 2000	Buchsbaum	2000	2000	5
MON-PR-GDATrans6Middle2000	GDA Parker River Middle Rd. vegetation transect #6 during year 2000	Buchsbaum	2000	2000	5
MON-PR-GDATrans7Middle2000	GDA Parker River Middle Rd. vegetation transect #7 during year 2000	Buchsbaum	2000	2000	5
MON-PR-GDATrans8AMiddle2000	GDA Parker River Middle Rd. vegetation transect #8A during year 2000	Buchsbaum	2000	2000	5
MON-PR-GDATrans8BMiddle2000	GDA Parker River Middle Rd. vegetation transect #8B during year 2000	Buchsbaum	2000	2000	5
MON-PR-GDATrans2Middle2002	GDA Parker River Middle Rd. vegetation transect #2 during year 2002	Buchsbaum	2002	2002	5

Dataset	Dataset Title	Lead PI	Begin Year	End Year	LTER Core Area
MON-PR-GDATrans3Middle2002	GDA Parker River Middle Rd. vegetation transect #3 during year 2002	Buchsbaum	2002	2002	5
MON-RO-GDAMusselSnail1999	GDA mussel and snail presence in Rowley River tidal creeks during 1999	Deegan	1999	1999	5
MON-RO-GDAMusselSnail2000	GDA mussel and snail presence in Rowley River tidal creeks during 2000	Deegan	2000	2000	5
MON-RO-GDAMusselSnail2001	GDA mussel and snail presence in Rowley River tidal creeks during 2001	Deegan	2001	2001	5
MON-RO-GDAMusselSnail2002	GDA mussel and snail presence in Rowley River tidal creeks during 2002	Deegan	2002	2002	5
CLIMATE					
MON-PR-Met15min2000	Year 2000, continuous 15 minute averages of meteorological station data	Hopkinson	2000	2000	1
MON-PR-Met15min2001	Year 2001, continuous 15 minute averages of meteorological station data	Hopkinson	2001	2001	1
MON-PR-Met15min2002	Year 2002, continuous 15 minute averages of meteorological station data	Hopkinson	2002	2002	1
MON-PR-Met15min2003	Year 2003, continuous 15 minute averages of meteorological station data	Hopkinson	2003	2003	1
MON-PR-Met15min2004	Year 2004, continuous 15 minute averages of meteorological station data	Hopkinson	2004	2004	1
MON-PR-Met15min2005	Year 2005, continuous 15 minute averages of meteorological station data	Hopkinson	2005	2005	1
MON-PR-Met15min2006	Year 2006, continuous 15 minute averages of meteorological station data	Hopkinson	2006	2006	1
MON-PR-Met15min2007	Year 2007, continuous 15 minute averages of meteorological station data	Hopkinson	2007	2007	1
MON-PR-Met15min2008	Year 2008, continuous 15 minute averages of meteorological station data	Hopkinson	2008	2008	1
MON-PR-Met15min2009	Year 2009, continuous 15 minute averages of meteorological station data	Giblin	2009	2009	1
MON-PR-Met15min2010	Year 2010, continuous 15 minute averages of meteorological station data	Giblin	2010	2010	1
MON-PR-Met15min2011	Year 2011, continuous 15 minute averages of meteorological station data	Giblin	2011	2011	1
MON-PR-MetDay	Daily averages of meteorological station data	Giblin	2000	2011	1
ESTUARINE PHYSICS					
PHY-PR-Dimension1993-1996	Physical dimensions of the Parker River channel, 1993-1996	Vallino	1993	1996	
PHY-PR-DYE-1993-1996	Rhodamine dye additions to Parker River	Hopkinson	1993	1996	
PHY-PR-SF6-1996	SF6 additions to Parker River, 1996	Hopkinson	1996	1996	
MON-BO-Sealevel-Monthly-MSL	Monthly mean sea level (1921-2011) Boston, MA, NOAA/NOS	Giblin	1921	2011	4
MON-PT-Sealevel-Monthly-MSL	Monthly mean sea level (1912-2011) Portland, ME, NOAA/NOS	Giblin	1912	2011	4
MON-PR-MBWatLevel2000	Year 2000, water level data, Middle Road Bridge, Parker River	Vallino	2000	2000	4
MON-PR-MBWatLevel2001	Year 2001, water level data, Middle Road Bridge, Parker River	Vallino	2001	2001	4
MON-PR-MBWatLevel2002	Year 2002, water level data, Middle Road Bridge, Parker River	Vallino	2002	2002	4

Dataset	Dataset Title	Lead PI	Begin Year	End Year	LTER Core Area
MON-PR-MBWatLevel2003	Year 2003, water level data, Middle Road Bridge, Parker River	Vallino	2003	2003	4
MON-PR-MBWatLevel2004	Year 2004, water level data, Middle Road Bridge, Parker River	Vallino	2004	2004	4
MON-PR-MBWatLevel2005	Year 2005, water level data, Middle Road Bridge, Parker River	Vallino	2005	2005	4
MON-PR-MBWatLevel2006	Year 2006, water level data, Middle Road Bridge, Parker River	Vallino	2006	2006	4
MON-PR-MBWatLevel2007	Year 2007, water level data, Middle Road Bridge, Parker River	Vallino	2007	2007	4
MON-PR-MBWatLevel2008	Year 2008, water level data, Middle Road Bridge, Parker River	Vallino	2008	2008	4
MON-PR-MBWatLevel2009	Year 2009, water level data, Middle Road Bridge, Parker River	Vallino	2009	2009	4
MON-PR-RT1AWatLevel2000	Year 2000, water level data, Rt 1A, Parker River	Vallino	2000	2000	4
MON-PR-RT1AWatLevel2001	Year 2001, water level data, Rt 1A, Parker River	Vallino	2001	2001	4
MON-PR-RT1AWatLevel2002	Year 2002, water level data, Rt 1A, Parker River	Vallino	2002	2002	4
MON-SO-IBYCWatLevel2000	Year 2000, water level data, Ipswich Bay Yacht Club, Plum Island Sound	Vallino	2000	2000	4
MON-SO-IBYCWatLevel2001	Year 2001, water level data, Ipswich Bay Yacht Club, Plum Island Sound	Vallino	2001	2001	4
MON-SO-IBYCWatLevel2002	Year 2002, water level data, Ipswich Bay Yacht Club, Plum Island Sound	Vallino	2002	2002	4
MON-SO-IBYCWatLevel2003	Year 2003, water level data, Ipswich Bay Yacht Club, Plum Island Sound	Vallino	2003	2003	4
MON-SO-IBYCWatLevel2004	Year 2004, water level data, Ipswich Bay Yacht Club, Plum Island Sound	Vallino	2004	2004	4
MON-SO-IBYCWatLevel2005	Year 2005, water level data, Ipswich Bay Yacht Club, Plum Island Sound	Vallino	2005	2005	4
MON-SO-IBYCWatLevel2006	Year 2006, water level data, Ipswich Bay Yacht Club, Plum Island Sound	Vallino	2006	2006	4
MON-SO-IBYCWatLevel2007	Year 2007, water level data, Ipswich Bay Yacht Club, Plum Island Sound	Vallino	2007	2007	4
MON-SO-IBYCWatLevel2008	Year 2008, water level data, Ipswich Bay Yacht Club, Plum Island Sound	Vallino	2008	2008	4
MON-SO-IBYCWatLevel2009	Year 2009, water level data, Ipswich Bay Yacht Club, Plum Island Sound	Vallino	2009	2009	4
MON-SO-IBYCWatLevel2010	Year 2010, water level data, Ipswich Bay Yacht Club, Plum Island Sound	Vallino	2010	2010	4
GIS & MAPS					
GIS-VA-PIEGIS	Longitude and latitude of various PIE-LTER sampling sites	Hopkinson	1994	present	
GIS-IP-ip30_info_anderson	Ipswich watershed land use 1971, 1985, 1991, 1999 according to MassGIS and Anderson Level 1	Pontius	1971	1999	4
GIS-IP-ip30_info_aspect	Ipswich Watershed aspect model.	Pontius	2002	2002	
GIS-IP-ip30_info_dem	Ipswich Watershed Digital Elevation Model using 30m grid.	Pontius	2002	2002	
GIS-IP-ip30_info_hydrology	Ipswich Watershed hydrology map to be used to generate a hydrologically corrected Digital Elevation Model.	Pontius	2002	2002	

Dataset	Dataset Title	Lead PI	Begin Year	End Year	LTER Core Area
GIS-IP-ip30_info_nutrientsamplesites	Ipswich Watershed single pixel locations of nutrient sampling sites in the Ipswich River Watershed.	Pontius	1999	1999	
GIS-IP-ip30_info_open_protection	Ipswich Watershed areas defined as protected and recreational open space.	Pontius	2002	2002	
GIS-IP-ip30_info_open_purpose	Primary use of Ipswich Watershed areas defined as protected and recreational open space.	Pontius	2002	2002	
GIS-IP-ip30_info_open_status	Status of Ipswich Watershed areas defined as protected and recreational open space.	Pontius	2002	2002	
GIS-IP-ip30_info_roads	Ipswich Watershed roads taken from MassGIS.	Pontius	2002	2002	
GIS-IP-ip30_info_slope	Ipswich Watershed slope model generated from Digital Elevation Model.	Pontius	2002	2002	
GIS-IP-ip30_info_townmask	Shows the entirety of towns that have area within the Ipswich River Watershed..	Pontius	2001	2001	
GIS-IP-ip30_info_towns	Shows the areas of towns that are located within the Ipswich River Watershed.	Pontius	2001	2001	
GIS-IP-ip30_info_townsvector	Shows the areas of towns that are located within the Ipswich River Watershed, vector form.	Pontius	2001	2001	
GIS-IP-ip30_info_wetlands	Shows locations of wetlands within the Ipswich study area.	Pontius	2001	2001	
GIS-IP-ip30_info_window	This map shows the extent of the Ipswich River Watershed study area.	Pontius	2001	2001	
GIS-p_arc_vector_01	Massachusetts State land use areas for the Parker and Ipswich River watersheds, 1971, 1985, 1991, 1999 (21 and 37 land use classifications)	Pontius	1971	1999	4
GIS-p_landuse7_1971_01	Massachusetts State land use for towns in the Ipswich River watershed for 1971, Anderson Level 1, 7 land use classifications.	Pontius	1971	1971	4
GIS-p_landuse7_1985_01	Massachusetts State land use for towns in the Ipswich River watershed for 1985, Anderson Level 1, 7 land use classifications.	Pontius	1985	1985	4
GIS-p_landuse7_1991_01	Massachusetts State land use for towns in the Ipswich River watershed for 1991, Anderson Level 1, 7 land use classifications.	Pontius	1991	1991	4
GIS-p_landuse7_1999_01	Massachusetts State land use for towns in the Ipswich River watershed for 1999, Anderson Level 1, 7 land use classifications.	Pontius	1999	1999	4
GIS-p_landuse21_1971_01	Massachusetts State land use for towns in the Ipswich River watershed for 1971, 21 land use classifications.	Pontius	1971	1971	4
GIS-p_landuse21_1985_01	Massachusetts State land use for towns in the Ipswich River watershed for 1985, 21 land use classifications.	Pontius	1985	1985	4
GIS-p_landuse21_1991_01	Massachusetts State land use for towns in the Ipswich River watershed for 1991, 21 land use classifications.	Pontius	1991	1991	4

Dataset	Dataset Title	Lead PI	Begin Year	End Year	LTER Core Area
GIS-p_landuse21_1999_01	Massachusetts State land use for towns in the Ipswich River watershed for 1999, 21 land use classifications.	Pontius	1999	1999	4
GIS-p_landuse37_1985_01	Massachusetts State land use for towns in the Ipswich River watershed for 1985, 37 land use classifications.	Pontius	1985	1985	4
GIS-p_landuse37_1991_01	Massachusetts State land use for towns in the Ipswich River watershed for 1991, 37 land use classifications.	Pontius	1991	1991	4
GIS-p_landuse37_1999_01	Massachusetts State land use for towns in the Ipswich River watershed for 1999, 37 land use classifications.	Pontius	1999	1999	4
GIS-p_mask_01	Plum Island Ecosystems Mask (Idrisi raster)	Pontius	1999	1999	
GIS-p_mask_vector_01	Plum Island Ecosystems Mask (Idrisi raster)	Pontius	1999	1999	
GIS-p_towns_01	Plum Island Ecosystems Towns (Idrisi raster)	Pontius	1999	1999	
GIS-p_towns_vector_01	Plum Island Ecosystems Towns (Idrisi raster)	Pontius	1999	1999	
GIS-p_watersheds_01	Plum Island Ecosystems Watersheds (Idrisi raster)	Pontius	2000	2000	
WAT-GIS-Anderson1_Landuse	Anderson Level 1 land use for the Parker, Rowley and Ipswich River watersheds years 1971, 1985, 1991 and 1999	Pontius	1971	1999	4
WAT-RGIS-120m-FlowDirection	Gridded flow direction (i.e. river network) of the watersheds draining to Plum Island Sound	Wollheim	2007	2007	
WAT-RGIS-120m-DirectDrainOrder	Gridded data set identifying for each pixel the stream order that drainage from the pixel initially enters into the Ipswich or Parker river network	Wollheim	2007	2007	
WAT-RGIS-120m-CellLength	GIS data layer is a gridded data set of cell length, corresponding with an estimate of river length, for rivers in Plum Island Sound watershed	Wollheim	2007	2007	
WAT-RGIS-120m-Distance2Ocean	GIS data layer is a gridded data set of the estimated distance (km) to ocean from each point in the gridded river network	Wollheim	2007	2007	
WAT-RGIS-120m-UpstreamArea	GIS data layer is a gridded data set of the contributing area to each grid cell for rivers in Plum Island Sound watershed	Wollheim	2007	2007	