PROJECT SUMMARY

Intellectual Merit: 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 climate, land use, and sea level. Our principal study site is the Plum Island Sound estuary located in the Acadian biogeographic province in eastern New England. Our study sites include the coupled Parker, Rowley, and Ipswich River watersheds, their tidal marshes, and the surrounding ocean of the Gulf of Maine.

Land use change and urbanization of coastal watersheds are altering both the magnitude and timing of the flow of materials and water to coastal ecosystems. These changes in flows from land, coupled with climate change and sea level rise, will have important, but still poorly understood consequences for the ways in which materials and energy are transformed in the coastal zone. It will also have important consequences for the people who value these ecosystems for food, recreation, and storm protection. The overarching question of this renewal addresses the ecological consequences of global change in the coastal zone: **How do external drivers, ecosystem dynamics, and human activities interact to shape organic matter and nutrient transformations in linked watershed and coastal ecosystems?**

The research we propose follows from our previous studies of biogeochemistry, food webs, and population biology in the Plum Island watersheds, estuary, and intertidal marshes. In this renewal we will put more emphasis on linkages and feedbacks between the component ecosystems, including the human dimension. We will also place a greater emphasis on the role of geomorphology and geomorphic change in ecosystem dynamics. To organize our research we have divided our study into four programmatic areas, each of which addresses an issue critical to answering our overarching question:

***Q1 Watersheds* -** How do human alterations of inter-basin material transfers, within-basin ecosystem connectivity, and geomorphology interact with climate to impact ecosystem regulation of water, organic matter, and nutrient fluxes through the watershed to the estuary, and how do these changes feed back to human behaviors that further alter watershed function?

***Q2 Marsh* -** Are the relative elevations of salt marshes at PIE in equilibrium with sea level, and if not, what are the consequences for primary production, biogeochemical cycling, and material exchanges between the marsh and estuary?

***Q3 Estuary* -** How do human activities and variations in climate that affect the coupling with watersheds, intertidal marshes, and the ocean shape organic matter and nutrient transformations in estuarine tidal creeks and bays?

***Q4 Higher Trophic Levels* -** What are the consequences of changes in ecosystem spatial configuration and dynamics for the structure and transfer of productivity in food webs, and for the function of higher trophic levels in estuarine ecosystems?

To address these questions we use a combination of approaches: 1) the collection of long-term data on key ecosystem drivers and ecosystem responses, 2) short and long-term experiments, 3) comparative ecosystems studies, and 4) modeling. All data collected by the PIE LTER are centralized and easily accessible to PIE-LTER scientists, local, regional and state partners, and the broader scientific community.

Broader Impacts: Our active educational and outreach program is greatly strengthened through partnerships with local educators and NGOs. We will continue to collaborate with Massachusetts Audubon and the Governor's Academy for our schoolyard program, which has brought hands-on science training to students in grades 5-12. "Salt marsh Science" currently serves more than 1000 students and 50 teachers a year. Over the next six years we plan to expand teacher training, and include a focus on environmental stewardship. Undergraduates will be served by intensive research experiences focusing on individual projects under the mentorship of PIE scientists. We expect that both undergraduate and graduate student involvement will increase with the addition of new PIs. PIE will maintain an active outreach program through our collaboration with many local and regional NGOs including the Gulf of Maine Institute, Essex County Greenbelt, the Ipswich River Association, and the Parker Clean Water Association. PIE scientists help bring scientific information into policy by serving as advisors to policy makers at the local, state, and national level, a role that continues to grow.

SECTION 1: RESULTS OF PRIOR SUPPORT

Plum Island Ecosystems LTER

Grant# OCE – 0423565 Funding 2004-2010 = $4,920,000 (excluding supplements)

The Plum Island Ecosystems LTER (PIE LTER) was established in 1998 and renewed in 2004. The principal study site is the Plum Island Sound Estuary, its coupled Parker, Rowley and Ipswich River basins, tidal marshes, and the coastal ocean of the Gulf of Maine. The goal of the program is to develop a predictive understanding of the long-term response of a connected land-estuarine ecosystem to changes in climate, land use, and sea level. In addition to gaining scientific knowledge, we aim to advance knowledge needed to develop policy and management strategies that will protect the natural resources of the coastal zone in the face of increasing pressure from human and natural changes.

During the past 5.5 years the project involved 180 individuals from 42 research and educational institutions. To date this grant has produced 110 peer reviewed publications and 16 dissertations and theses (Table 1.1 Supplementary Docs.). Data from our long-term monitoring activities, as well as that of shorter term research activities, are posted on-line. A list of LTER datasets and their documented use is shown in Table 1.2 (Supplementary Docs.) .

Our overarching question for the last 6 years has been: **How will trophic structure and primary and secondary productivity in estuaries be affected by changes in organic matter and nutrient loading and hydrodynamics caused by changing land use, climate, and sea level?** To address this question the research team was organized around five programmatic areas (watershed, marshes, estuarine water column, benthos and higher trophic levels). We present selected research results below followed by results of our integration, synthesis and modeling activities.

WATERSHED – What is the magnitude and long-term pattern of freshwater runoff and organic carbon and nitrogen and inorganic N loading from the watershed to the estuary?

Human activities now dominate the N cycle in our watersheds and significantly impact the hydrologic cycle. Human diversion of water from the watershed now equals ~20% of annual runoff but the impact of this diversion has been largely offset by increased precipitation due to climate change. As a result, annual runoff to the estuary over the last century has not detectably changed (Claessens et al. 2006). Human N input via food/waste dominate the contemporary N budget of the watershed (Williams et al. 2004). Most of the basin-wide N inputs are retained on land (>80%), though retention declines with increasing imperviousness (Williams et al. 2004, Wollheim et al. 2005, Filoso et al. 2004) because flow paths bypass soils during storm events (Pellerin et al. 2008). The river network is highly effective at denitrifying DIN inputs under low flow (> 90% of inputs from land), and shows greater than predicted retention at high flows, potentially indicating that floodplain ecosystem are important regulators of nutrients at higher flows (Wollheim et al. 2008a).

Whole ecosystem tracer additions in PIE streams revealed that the denitrification becomes less efficient as N concentrations increase, which is consistent with other stream studies (Mulholland et al. 2008). In other experiments we found the relative size of transient storage zones increases with stream size, while exchange parameters remain constant (Briggs et al. in press). Experimental in-situ manipulations of O_2 and DOC indicate that O_2 is the primary regulator of N forms and N cycling, while DOC levels fuel process intensity. This suggests that a better understanding of O_2 dynamics may be needed to understand DOC vs. nitrate relationships across different streams (Thouin et al. 2009).

Our work with spatially distributed models has focused on understanding these processes at the network scale. Large rivers are potentially important N removal sites at network scales because total benthic surface areas typically remain similar across stream size (Wollheim et al. 2006, 2008). Loss of denitrification efficiency results in a declining importance of small relative to large rivers in networks as N loading increases (Mulholland et al. 2008, Wollheim et al. 2008). An enhanced network model that incorporates transient storage dynamics suggests that hyporheic zones dominate N removal at network scales, despite relatively slow exchange between surface water and the hyporheos (Stewart 2009).

Land use change models shows that if trends of deforestation since 1970 continue, 40% of the existing forest will be lost by 2050 (Pontius and Neeti 2009). About 14% of the study area consists of manicured grass, and about half of this is lawns of private residences. We also found that town-level residential water-use restrictions are increasing in duration and frequency, (controlling for climate variation), and that some state-level water- and land-use policies appear to be driving this trend, whereas other policies may be mitigating the trend (Polsky et al. 2009; Hill and Polsky 2005, 2007).

MARSHES –How are tidal marsh processes and their connections to estuarine waters regulated by sea level, storms, and water and material inputs from land and sea?

Research at the PIE LTER has confirmed that sea-level anomalies affect salt marsh primary productivity. This led to the development of a model that explains how marsh landscapes maintain equilibrium with sea level (Morris et al. 2002, Mudd et al. 2004, Morris et al. 2005, Morris 2005, Morris 2006, Morris 2007). Marsh primary productivity is strongly related to variations in flooding and salinity during the growing season (Morris 2000, Morris et al. 2002) and to temperature (Kirwan et al. 2008). The estuarine salinity gradient migrates in response to changes in freshwater discharge and sea level, and this affects ammonium export and import by marshes (Koop-Jakobsen and Giblin 2002; Weston et al. accepted). Increased sea level rise is likely to promote the migration of salt marshes upriver and to reduce the extent of tidal fresh and brackish marshes (Buchsbaum et al. 2006). PIE salt marshes are disintegrating due to a combination of lateral erosion and marsh ponding (Cavatorta et al. 2003), which is likely due to sea-level rise and reduced sediment loads as a consequence of reforestation of the watershed following abandonment of agriculture in New England. Disintegration initially results in an increase in marsh edge (Johnston et al. 2003), where there is considerable drainage of marsh porewater. Thus, increased sea-level rise is likely to increase porewater drainage which is a significant source of inorganic and organic nutrients for the planktonic sub-system (Raymond and Hopkinson 2003, Gardner & Gaines 2008, Wilson and Morris, in prep.). The remaining high marsh at PIE appears to be maintaining its elevation as a consequence of cannibalization (Wang et al. 2009), i.e. eroded peat from the margins is deposited on the remaining surface. To examine how changes in marsh elevation alters sediment N cycling we investigated the relative importance of denitrification vs. dissimilatory nitrate reduction to ammonium. To facilitate this, we developed a new approach that allows denitrification and DNRA to be measured in the marsh rhizosphere (Koop-Jakobsen and Giblin 2009b).

ESTUARINE PLANKTONIC SYSTEM – How do planktonic community structure and production respond to changes in organic matter, nutrients and water fluxes?

The estuary is characterized by strong spatial gradients along its length including water residence time, community structure, the relative importance of pelagic and benthic primary production (Tobias et al. 2003a), bacterial community structure (Crump et al. 2004, Crump and Hobbie 2005) and patterns of metabolism (Vallino et al. 2005). Phytoplankton blooms occur in the oligohaline part of the estuary during midsummer when water residence time is high. When residence time is short, phytoplankton blooms never occur. Instead the base of the foodweb shifts to benthic microalgae (Tobias et al. 2003a). The phytoplankton community has a greater freshwater component in the upper estuary but is dominated by marine forms seaward. Shifts in bacterioplankton community composition along the salinity gradient are related to residence time and bacterial community doubling time in spring, summer, and fall. Freshwater and marine populations represent a large fraction of the bacterioplankton community in all seasons (Crump and Hobbie 2005), however, a unique estuarine community forms at intermediate salinities when bacterial doubling time is shorter than water residence time (Crump et al. 2004).

The estuary is heterotrophic along its entire length, but especially during times of high river discharge (Vallino et al. 2005). Seasonal patterns of GPP are driven primarily by variations in residence time, temperature and radiation, while R is driven primarily by variation in marsh flooding, temperature, GPP, and residence time. Bioassay and biomarker analyses suggest that allochthonous watershed inputs of OC meet NEP demands only in the upper 5 km of the estuary. Biomarkers (Raymond and Hopkinson 2003) show a large internal input of DOC from phytoplankton and marsh grass and that the estuary exports both watershed and internally-derived organic carbon to the continental shelf. Mass balance suggests that 1 to 45% of marsh NPP is required to sustain estuarine heterotrophy. While analysis of ^{14}C shows an internal input of old particulate C, presumably from eroding marsh peat, it appears to pass unaltered to the ocean (or perhaps onto the marsh platform –see Marsh research section). One mechanism we think is particularly important in transferring marsh C to the water column is creekbank porewater drainage. Gardner and Gaines (2008) determined creekbank drainage to average about 160 m^3 yr^{-1} per m of edge. Scaled to creekbank edge length throughout the estuary and porewater DOC concentrations, drainage volume and C input exceeds that from the entire Parker River. However, we also find compelling evidence that much of the estuarine heterotrophy arises from respiration on the marsh platform, as the sum of water column and benthic respiration is only half of free water measures of respiration. That much of the "estuarine respiration in water" must occur on the marsh proper, as opposed to in tidal creeks, agrees with similar observations for Georgia estuaries (Wang and Cai 2004).

ESTUARINE BENTHOS – How do benthic recycling of nutrients and processing of organic matter respond to changes in freshwater runoff and the quality and quantity of organic matter inputs? Seasonal and inter-annual patterns of respiration in the upper Parker Estuary are well correlated with temperature, while, ammonium release is better correlated with salinity (Giblin et al. accepted). Salinity controls ammonium release through several mechanisms. First, salinity directly affects ammonium release through ion exchange (Weston et al. accepted). Second, salinity has a large indirect effect on rates of microbial processes including, nitrification, denitrification, and dissimilatory nitrate reduction to ammonium (DNRA) (Giblin et al. accepted). During summer and early fall, when salinity is high, nitrification rates decrease by nearly an order of magnitude compared to values measured in April. The numbers of ammonium oxidizing bacteria (AOB) also decrease by nearly ten fold from spring to fall, although the overall structure of the AOB community does not change (Bernhard et al. 2005, 2007). Lower nitrification rates decrease rates of coupled nitrification/denitrification so that N losses decrease over the summer. At the same time the preferred pathway for nitrate reduction shifts from denitrification (N_2) to DNRA where the end product is ammonium. These changes all results in enhanced N release from sediments and may contribute to the large mid- to late-summer phytoplankton blooms we observe. At the mid-estuary site, which has a large bivalve population, we see a very different pattern. Here salinity changes are more modest and do not exert a strong control on N cycling. Ammonium release is well correlated with benthic respiration throughout the year. In contrast to the upper estuary where salinity variations control N cycling, variability at the mid-estuarine sites is largely driven by animal abundance. We also expanded our studies of N cycling pathways onto the marsh platform and found that DNRA and denitrification are of equal importance as a nitrate sink (Koop-Jakobsen and Giblin 2010), while anaerobic ammonium oxidation is a minor pathway (Koop-Jakobsen and Giblin 2009a).

HIGHER TROPHIC LEVELS – How do the structure and function of higher trophic levels respond to changes in land, atmospheric and oceanic forcing as well as fisheries harvest? Our work has shown that higher trophic levels play an important role in controlling transfers of energy in PIE food webs and in determining estuarine response to environmental change (see Integrating Experiments below). Understanding the movements of top predators is key to predicting both their impacts on estuarine processes and their response to climate change. A recent advance, acoustic telemetry (remotely sensed tags), allows repeated observations of individuals and has provided these new insights into striped bass (a top predator) within-estuary foraging and long-distance migration. Striped bass traveled thousands of kilometers passing by other estuaries to become repeat summer residents in PIE (Mather et al. 2009, 2010) and individuals partitioned into two distinct feeding groups – those that foraged in tidal rivers and those that foraged in the open bay (Pautzke et al. 2010). These findings contradict the common assumptions that striped bass move opportunistically and randomly in the estuary, (Mather et al 2003) and suggest that bass may be more important top-down controls on prey populations than previously thought. Additionally, we have shown an unexpectedly tight connection between specific summer feeding and overwintering estuaries. Almost 2/3^{rds} of the PIE summer resident striped bass wintered in Delaware Bay and over 60% of these fish returned to be PIE residents the next year (Mather et al. 2010). This confirmed our result obtained from using anchor tags that PIE tagged bass returned 2 to 7 years later (Mather et al. 2009). Our results contradict the assumption that bass show no fidelity to foraging estuaries within a year and randomly use different estuaries in subsequent years.

Landscape level differences in ecosystem characteristics may be important drivers of production transfer to higher trophic levels. In salt marshes, when mummichogs were caged in fresh, brackish, and marine marsh areas, and then transplanted between habitats, growth was highest in fresh and brackish areas where they had more access to the marsh platform and to terrestrial prey with higher protein content (Haas et al. 2009). Isotope characteristics of wild fish suggest some fish may be making much longer intra-estuarine movements (>1 km) to maximize growth than previously thought (Haas et al. 2009; Logan et al. 2006). In rivers, anadromous river herring are an important component of both freshwater and estuarine systems, and can serve as important conservation education tools (Frank et al. 2009a). Our acoustic tagging work in the Ipswich River suggests that restoration of decimated herring populations by transplanting spawning stock from other rivers may be problematic. Transplanted herring tended to return to estuarine locations rather than proceed upstream towards spawning areas (Frank et al, 2009b, c).

INTEGRATING EXPERIMENTS -We have two on-going large-scale experiments that integrate among our program areas. These experiments manipulate plant resources and examine resulting changes in biogeochemical cycles and food webs. The first experiment is a long-term removal of marsh vegetation by haying (Buchsbaum et al. 2009). Marsh haying, despite altering plant species composition, resulted in only minor changes in the food web and had no effect on the abundances of breeding birds. The second experiment is a chronic N additions to salt marsh creeks designed to quantify the effects and interactions of increased nutrients and reduced abundance of a key fish on the function and sustainability of salt marsh ecosystems (TIDE experiment; Deegan et al. 2007). Contrary to theory and prior caging experiments, the mummichog is a weak interactor in the algae-based trophic cascade in creeks (Deegan et al. *2007)*, but exerts strong trophic control in the detrital food web on the marsh platform (Johnson et al. 2009; Galvan et al. 2008). This suggests 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 (Fleeger et al. 2008, Johnson and Fleeger 2009, Johnson et al. 2009). Although chronic nitrogen enrichment to creeks resulted in no large-scale plant community changes, we measured ecologically significant changes in ecosystem nitrogen cycling (Drake et al. 2009; Koop-Jakobsen & Giblin 2010).

SYNTHESIS AND MODELING -The synthesis and modeling component of PIE-LTER focused on two main areas during the last funding cycle: 1) coupled estuarine circulation and biogeochemistry modeling and 2) advancement of our distributed metabolic network model optimized by maximum entropy production (MEP). A very high resolution (sub meter) version of our 2D finite element model for PIE was developed for Sweeny Creek to examine how our long-term marsh fertilization experiment creates shifts in primary producer dominance. The transport model has been completed and coupled to a biogeochemistry model that focuses on capturing N flow through the four functional primary producers: phytoplankton, benthic microalgae, macroalgae, *Spartina*. As the long-term fertilization experiment continues, we will use this high-resolution model to test ideas on how primary producer abundances change as a function of N-loading, shading and local transport characteristics. At the whole estuary scale, we have been developing FVCOM (Finite-Volume Coastal Ocean Model: Chen *et al.* 2003, Chen *et al.* 2004) for PIE using a high resolution bathymetry model based on our LIDAR data for the estuary. We have been collaborating with Chen's group at UMass Dartmouth to accurately simulate 3D circulation in PIE estuary. Because of the connection between Plum Island Sound and the Merrimack River, we have extended the domain of the model to incorporate both the local offshore current as well as the Merrimack River, where boundary conditions are obtained from FVCOM running in the Gulf of Maine. We have found, from drifter simulations and model guided observations, that a significant residual clockwise circulation develops between the Merrimack R. and PI Sound, where water in the Sound flows northward into the Merrimack R., then tracks southerly along the shore, and re-enters the Sound via its southern mouth (Zhao *et al.* 2009). Our results show that PI Sound and the Merrimack R. have a much tighter coupling than previously appreciated.

Although we have developed several classic compartment-type biogeochemistry models for the estuary (Hopkinson and Vallino 1995, Vallino 2000, Wan and Vallino 2005, Vallino *et al.* 2005) and watershed (Filoso *et al.* 2004), we have also been developing a metabolic approach (Vallino *et al.* 1996, Vallino 2003) that relies on the principle of maximum entropy production (Dewar 2003, 2005, 2009) to explain ecosystem biogeochemistry. During this cycle our major accomplishments include, a direct means of modeling entropy production rates from biogeochemical reactions, a spatiotemporal optimal control algorithm to determine how biological structure is allocated to distributed metabolic networks expressed by microbial communities, a mathematical definition that distinguishes living from nonliving systems, and how MEP arises from Darwinian competition and the establishment of a long term (> 4 years now) microcosm experiment for testing MEP hypotheses (Vallino 2009).

SUPPLEMENTARY FUNDING -Equipment **-** All programmatic elements of PIE have benefited from equipment supplements, which have allowed us to expand the temporal and spatial coverage of our long-term monitoring efforts, improved our laboratory capability and enhanced our data management. Social Science – Integration of social science into PIE was greatly advanced by social science supplements to Colin Polsky (Clark University) in 2007, 2008 and 2009. These awards, coupled with the student REU support to Polsky and PIE researcher Pontius, allowed the Clark-PIE team to develop the training to build a strong social science PIE team, and purchase the physical infrastructure needed for high-resolution (~0.5m) landscape mapping, and helped to launch several cross-site initiatives (see below).

CROSS-SITE SCIENCE AND NETWORK ACTIVITIES - PIE scientists have been involved in national synthesis activities including: the Lotic Interstream Nitrogen Experiment (LINX), a NCEAS funded project examining ecosystems services, the Denitrification Research Coordination Network, and the Consortium of Universities for the Advancement of Hydrologic Sciences (CUASHI). PIE researchers have participated in NEON planning, including the support of site specific planning for a New England suburban relocatable site within the Plum Island watersheds. Largely suburban Essex and Middlesex counties, which encompass the Plum Island watersheds, are included in a cross site, rural-to-urban (Hubbard Brook to Baltimore LTER) analysis of county-level potential for carbon storage and carbon emissions in the northeastern US sponsored by the Hubbard Brook Research Foundation. The integrated social-natural science PIE group (Polsky, Pontius, Wollheim, Hopkinson) has launched a national (multi-site) LTER mini-network of integrated socio-ecological research that operates using a shared research design. Pontius is also co-leading (with G. Kofinas and N. Sayre) a multi-LTER-site effort to study land change maps, emphasizing PIE and GCE at present. Hopkinson and Polsky are participating in a multi-LTER effort to examine coastal vulnerabilities associated with climate change.

DEVELOPMENT OF HUMAN RESOURCES AND OUTREACH Our K-12 schoolyard program, “Salt Marsh Science”, directed by Elizabeth Duff of the Massachusetts Audubon Society serves grades 5-12 in eleven towns. Ms. Duff was recently awarded a “Gulf of Maine Institute Visionary Award” for this work. Undergraduates are served through hands-on internships, projects and field trips. Thirty-two graduate students and ten post-doctoral investigators participated over the last 6 years Outreach is a very important part of our mission. We have close connections with or serve on boards of a variety of NGOs whose mission is broadly defined as environmental education. We communicate regularly with policy makers on issues ranging from water management to fisheries. (see Section 5).

SECTION 2: PROPOSED RESEARCH

INTRODUCTION

Coastal ecosystems form a dynamic and important boundary between the continents, oceans and the atmosphere. 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 (Hedges et al. 1997, Aller 1998, McKee 2003, Seitzinger & Harrison 2008). Coastal ecosystems are also highly valued by people and the site of some of the world's most intense population growth and activity (Nicholas & Small. 2002; Crossett et al. 2004: Scavia and Bricker 2006). The increasing human use of coastal watersheds, coupled with climate change and sea level rise, will have important, but still poorly understood, consequences for the transformations of materials and energy in the coastal zone. It will also have important consequences for the people who value these ecosystems for food, recreation and storm protection.

The Plum Island Ecosystems (PIE) LTER, begun in 1998, is an integrated program that aims to increase our basic understanding of the hydrology, biogeochemistry and food webs of land-margin ecosystems. Our 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 climate, land use, and sea level. Our principal study site is the Plum Island Sound estuary located in the Acadian biogeographic province in eastern New England. Our study sites include the coupled Parker, Rowley, and Ipswich River watersheds, the estuarine areas and open bay, tidal marshes, and the coastal ocean of the Gulf of Maine (Fig. 2.1). We extend our understanding to other coastal ecosystems through comparative studies and modeling.

Over the last century land use in the PIE watersheds has changed substantially. Watersheds underwent a period of reforestation as agricultural fields were abandoned at the turn of the century. This was followed by a loss of forest cover after the Second World War, as population increased and suburban areas expanded rapidly (Schneider and Pontius 2001). With suburbanization, human uses of water increased, and at the same time, natural patterns of precipitation, and evapo-transpiration also changed (Claessens et al. 2006). The extensive tidal marshes, the largest remaining in the northeastern United States, were not directly developed but were indirectly affected by changes in water, nutrient, carbon and sediment loads due to land use change. Historical data is scant but food webs have probably been altered by human harvest. The creation of barriers to migration and spawning has lead to drastic declines in anadromous fish. Coupled with these changes within the watershed are large-scale regional changes such as an increase in the amount of storms (Hayden and Hayden 2003), and rising sea level. *These changes are occurring world wide 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 develop a broad conceptual framework.

CONCEPTUAL FRAMEWORK

Our conceptual framework for the LTER has evolved over the past 12 years to reflect our better understanding of how coastal ecosystems respond to changes in climate, sea level rise and changing land use. In PIE-I we developed a conceptual model (Fig 2.2) that delineated our six programmatic areas. We retained this conceptual model during PIE II when our overarching question was "*How will trophic structure and primary and secondary productivity in estuaries be affected by changes in organic matter and nutrient loading and hydrodynamics caused by changing land use, climate and sea level*". This question, however, held the implicit bias that *outside forcing* (climate, land use change, sea level rise) alters *key drivers* (water, nutrients, organic matter), and that changes in these drivers cause an *internal* ecosystem response. The question did not specifically acknowledge that the internal responses of the coastal ecosystems to such changes may in turn lead to positive or negative feedbacks that alter these same drivers. In addition, although land use change has been a key component of our research since the beginning, the complex dynamics among flows of water and materials, human activity, and ecosystem responses was not explicitly incorporated into our conceptual framework. Finally, synthesis between program areas was designed to be achieved through integrative experiments and modeling, but most programmatic areas did not emphasize understanding linkages between systems other than by hydrology and material fluxes.

In this renewal we intend to address some of these important issues. Our overarching question is: **How do external drivers, ecosystem dynamics, and human activities interact to shape organic matter and nutrient transformations in linked watershed and coastal ecosystems?** We include organic matter transformation in a broadest sense, from microbial respiration to changes in food webs.

This new question offers a common framework in which to: (1) examine linkages and feedbacks between ecosystems in more detail; (2) incorporate the role of geomorphology and geomorphic change on ecosystem dynamics; and (3) incorporate the human dimension in a dynamic way. This evolution in focus will also address the recommendation of the three year review committee that PIE begin a broader synthesis between program areas. Finally, this question brings the PIE-LTER into the general framework recommended by the LTER Research Initiatives Subcommittee to NSF for “Integrating Science for Society and the Environment” (ISSE).

Feedbacks and Linkages

In this renewal we put more emphasis on understanding how systems are linked beyond hydrology and material fluxes and how responses within an ecosystem feed back and change external forcing. Anadromous fish migration, the harvest of salt marsh hay, and clamming are examples of ways in which carbon and nutrients from “downstream” ecosystems can move independently of water to “upstream” ecosystems. In some cases linkages such as these may be quantitatively important in their own sake. In others, they may be important because of the ways in which they feed back on human choices about landscape management. For example, a decrease in anadromous fish may precipitate dam removal, which in turn alters both the timing and magnitude of freshwater inputs, nutrients, and sediments to the estuary. Dam removal may then lead to a greater movement of sediment from the estuary to the marsh, facilitating the ability of the marsh to keep up with sea level. There are many such linkages and feedbacks which could and should be explored. In this renewal we have chosen a few key linkages that have emerged from our past research as important.

The role of freshwater flows and geomorphology

Over the last six years we have characterized the estuary as having different “spheres of influence” that were determined by the hydrologic template (Fig 2.3). Hydrology plays a key role because the influence of organic matter and nutrient inputs on estuarine food webs is dictated by the time scale of processes compared to water residence time. Freshwater discharge alters water residence time, which can range from 2 to 34 days (Vallino and Hopkinson 1998). Hydrology also determines the salinity structure, which may play as great a role as residence time in structuring some aspects of the PIE. In concert with these different hydrologic regimes we found that the upper areas of the Rowley, Parker and Ipswich, each have different food web structures and these differ from the shallow areas of Plum Island Sound (Hughes et al. 2000; Tobais et al. 2003b, Fig 2). The importance of algal blooms (Holmes et. al 2000), key aspects of the nitrogen cycle (Tobias et al. 2003; Giblin et al. accepted; Weston et al. accepted), fish communities (Haas et al. 2009); microbial communities (Bernhard et al. 2005; Crump et al. 2004; Crump and Hobbie 2005); and salt marsh vegetation (Morris 2006) all differ spatially and show different responses to changing drivers depending upon their location in the estuary.

The concept of a hydrologic or geomorphic template is not a new one. Estuarine ecologists have long recognized the role that hydrology plays in estuarine dynamics (e.g., Prichard 1952; Lucas et al. 1999; Ferreira et al. 2005 and refs therein). There have been many attempts to classify estuarine types or estuarine “signatures,” either according to single factors such as residence time (Ketchum 1954), tidal range (Alvera-Azcarate et al. 2003), or salinity regimes (Bulger et al. 1993; Jassby et al. 1995) or by more complex hydrodynamic metrics (Jay et al. 2000; Geyer et al. 2000). These classifications have been very useful, and will continue to be so for a wide variety of current management issues such as eutrophication (e.g. Scavia and Bricker 2006) and fisheries management (Jassby et al. 1995). However, classification do not incorporate any feedbacks that will allow the "template" to change with changing forcing from land and ocean and thus have a limited ability to predict long-term responses.

Over the last 6 years we have made progress in developing a fully functioning 3D hydrodynamic model that allows us to move beyond simple classification schemes and fully describe the hydrodynamics and salinity structure of the estuary. This model, when coupled with biogeochemical and food web models, provides a way to examine the ecosystem response to changes in forcing and is allowing us to greatly expand our understanding of short-term dynamics. In developing these linked models we have realized that *while hydrodynamics explain many of the spatial patterns we see, hydrodynamics is linked with a more complex set of relationships, such as marsh/water ratio, edge, turbidity, and sedimentation that impact estuarine productivity and processes. These traits are determined in part by the interaction of hydrology with the underlying geomorphology*.

In this renewal we specifically ask questions relating to the role of geomorphology and geomorphic change on ecosystem dynamics (Fig. 2.4). Geomorphic change has always been a key question in PIE marsh research, and implicit in the research on habitat quality done by the higher trophic level group. This new emphasis across program areas has been driven in part by the fairly large changes we are seeing at PIE in the underlying geomorphic structure. For example, river channels in PIE watersheds are being significantly altered by the return of beavers, sediments and water inputs to the estuary will be changed by the planned removal of several mill dams, and, between 2000 to 2007 the central section of the barrier island that makes up Plum Island eroded more than 4 m/yr because of storms. These changes will obviously feedback on ecosystem structure and function, and in turn, changes in the ecosystem will feedback on the forces changing geomorphology (Reed 2000; Torres et al. 2006; Fisher et al. 2007; Day et al. 2008). Some of these feedbacks, such as changing vegetation and channel development (Reed 2000, Marani et al. 2006; Mudd et al. 2009) will be internal. Others, such as the removal of mill dams and beaver dams or beach nourishment, will be directly controlled by humans but will also be influenced by internal readjustments to geomorphology. We obviously cannot address all of these new issues but we feel it is critical to incorporate them into our thinking and our research framework. Our efforts in this area are further strengthened by work being done in PIE by geomorphologists Sergio Fagherazzi and Duncan Fitzgerald (Boston University). PIE investigators are directly collaborating with B.U. coastal geomorphology group and we have supplied LIDAR data, bathymetry and model grids to the both groups.

The human dimension

In this renewal we also place greater emphasis on the human dimension and the feedbacks between changes to natural ecosystems and human decisions on land use and natural resource management. PIE's research program includes a small but growing component in human dimensions. Much of this work is concentrated in the watershed where land-use change is a critical driver of water and material flows. In the last renewal we used mapping and modeling to understand past patterns and future directions in land use and forest cover (Pontius et al. 2003; 2004; 2006) and their impacts on watershed hydrology and biogeochemistry (Filoso et al. 2004). In this proposal we will expand this approach by building on recent work funded by a major external NSF (CHN, 2007) received by Polsky at Clark U. and PIE researchers Hopkinson, Wollheim and Pontius, and three PIE social science supplements awarded to Polsky and Pontius. We will add social survey techniques, and fine resolution remote sensing to develop spatial maps of how people influence the magnitude and distribution of water and nutrient transfers. We will also use historical investigations to examine how human use and alterations of watersheds and stream networks and the inter-basin transfers of water and other materials have changed over time. Although the social science research in PIE is focused on the watershed we have explicitly acknowledged the role that human feedbacks play in all of our research questions (Fig. 2.4).

PROPOSED RESEARCH QUESTIONS - To address our overarching question we have arranged our research around four major questions that correspond to programmatic areas. Synthesis and modeling form a fifth programmatic area. In the following section each of these questions is further broken down into three sub-questions. One question focuses within the program area and builds upon our understanding of that area. To facilitate synthesis, each program area has also developed one question that specifically addresses *linkages and feedbacks* between systems, and one that addresses *the role of geomorphology and geomorphic change*.

Q1 Watersheds - How do human alterations of cross-boundary material transfers, within-basin ecosystem connectivity and geomorphology interact with climate to impact ecosystem regulation of water, organic matter and nutrient fluxes through the watershed to the estuary, and how do these changes feed back to human behaviors that further alter watershed function?

Q2 Marsh **- Are the relative elevations of salt marshes at PIE in equilibrium with sea level, and if not what are the consequences for primary production , biogeochemical cycling, and material exchanges between the marsh and estuary?**

Q3 Estuary - How do human activities and variations in climate that affect the coupling with watersheds, intertidal marshes and the ocean shape organic matter and nutrient transformations in estuarine tidal creeks and bays?

Q4 Higher Trophic Levels - What are the consequences of changes in ecosystem spatial configuration and dynamics for the structure and transfer of productivity in food webs, and the function of higher trophic levels in estuarine ecosystems?

APPROACH

PIE LTER has always used a combination of approaches to address our research questions and hypotheses: 1) long-term "core" measurements supplemented with shorter term, question-focused data collections, 2) field experiments, 3) comparative ecosystems studies, and 4) modeling. We briefly highlight the approach we will take in this next funding cycle.

Long -term core measurements: Our core measurements are designed to detect long tem changes in major drivers (climate, sea level), material stocks and fluxes (water, nutrients, carbon, sediment), and key biotic (primary production, food web, biogeochemical cycling, respiration) and abiotic (sedimentation, porewater drainage) responses. Our core measurements fit with the 5 LTER core areas and are directly related to our research questions (see Table 2.1) and remain relatively unchanged. New "core" measurements that are proposed for the next funding cycle are described in the approach section for specific research questions. Long-term measurements are supplemented by shorter data collections efforts designed to answer specific research questions as described below.

Field Experiments: Our program includes 4 long-term field manipulations. The first long-term experiment is the removal of the above ground biomass by harvesting salt marsh hay. Haying has been carried out in our marshes since colonial times and is still going on today. This manipulation is a detritus removal experiment, which is similar to the detritus removal experiments being carried out at a number of other LTER sites. The second is small-scale marsh factorial fertilization that was begun with PIE-I. These experiments are similar to those that have been set up in marshes all over the world.

The third is a whole tidal creek fertilization and foodweb manipulation experiment was established at PIE with separate NSF funding in 2003. It was designed to examine the effects of increased nutrient loading on coupled marsh-creek ecosystems and determine how nutrient enrichment interacts with changes in the abundance of key species at higher trophic levels. This is an important integrating experiment and provides a wealth of information upon which to further refine and test our models. This experiment will continue until at least 2012. Finally, in addition to the two controlled nutrient additions experiments we take advantage of large gradients in nitrate concentrations set up by wastewater disposal in the Ipswich Estuary.

Comparative Ecosystems Research: When ever possible we work with others both inside the LTER network and outside to compare our findings to those of other locations. This allows the community to test the generality of conclusions, and ensure that models be tested rigorously. As mentioned above, the detritus removal and fertilization experiments are two examples of experiments that are used in comparative studies. Over the last cycle we have worked with other scientists to standardize measurements to work toward inter-comparisons. For example, marsh sediment elevation tables and feldspar marker horizons (Boumans and Day 1993; Cahoon et al. 1995) have now been deployed at numerous marsh sites including GCE and VCR as well as at North Inlet SC, and in the Wells ME NERR site. Jim Morris has been active in efforts to synthesize this data. We have been communicating with VCR and other coastal sites as we deploy our flux tower to allow for a robust inter-comparison. The watersheds group has been involved in cross-site inter-comparisons on N cycling in streams.

Modeling: Each of the programmatic elements has a modeling component but we also rely on models to help us integrate research across programmatic areas. Our ability to model the hydrodynamic links between the Plum Island Ecosystems greatly advanced in the last funding cycle and we have begun to couple the movement of water with the movement of materials and changes in biogeochemical processes. This effort will be further informed by the research on feedbacks and linkages (human and biophysical) taking place during this cycle. We do not expect to be able to couple geomorphological models of PIE's ecosystems to hydrologic and biogeochemical models during this next funding cycle but this is our long term goal.

PROPOSED RESEARCH: WATERSHEDS

Question 1: How do human alterations of cross-boundary material transfers, within-basin ecosystem connectivity and geomorphology interact with climate to impact ecosystem regulation of water, organic matter and nutrient fluxes through the watershed to the estuary, and how do these changes feed back to human behaviors that further alter watershed function?

Rationale. Human activity leads to a softening of watershed boundaries through the transfer of materials that sustain human populations (Lookingbill et al. 2009). As a result, water, carbon, and nutrient budgets are severely perturbed in watersheds with concentrated human activity, greatly impacting watershed-estuary linkages (Claessens et al. 2006, Williams et al. 2004, Weiskel et al. 2007). Human activity also alters natural ecosystem processes that regulate fluxes through the watershed by altering landscape geomorphology and connectivity of watershed subsystems (Grimm et al. 2008). These changes affect the mobilization of materials and their fates, which can either magnify or attenuate the degree of downstream impact caused by increased cross-boundary transfers. For example, flashier hydrology in urban catchments (Pellerin et al. 2008) can lead to greater flooding of downstream floodplains that have a high N retention capacity (Johnston et al. 2001), attenuating the increased N load typical of urban catchments (Wollheim et al. 2005) (Fig. 2.5). Altered biogeophysical conditions, in turn, can lead to feedbacks that modify human activity, as for example when towns respond to low flow conditions with short or long term drought response measures (Polsky et al 2009, Hill and Polsky 2005, 2007), further affecting cross-boundry transfers, within-basin processes, and watershed to estuary linkages; these interactions are not new (e.g., Russell et al 1970) but they appear increasingly coupled. All of these dynamics take place within the context of climate variability and change, and require an understanding of processes over a range of climate conditions (e.g. Kaushal et al. 2008). Our goal in the watershed component of the PIE-LTER is to understand the drivers of human actions, the consequences of human actions on ecosystem processes, the resulting impact on the flux of materials from the watershed to the estuary, and the feedbacks to human activity (Figure 2.6). We will address three specific research questions:

Specific Research Question: **1A)** *What are the social drivers of land use and land cover, what are the resulting spatial and temporal patterns of land use and land cover, and how do these patterns influence the magnitude and distribution of cross-basin transfer of water and nutrients?*

Human activity influences a myriad of ecosystem properties across a range of scales (Liu et al. 2007, Rindfuss et al. 2008, Gragson and Grove 2006). At the watershed or regional scale, land use and land cover are dominant drivers that influence water and nutrient budgets, which in turn shape ecosystem structure and function in down slope systems that are hydrologically connected. Understanding the forces shaping the spatial and temporal patterns of land use and land cover, including short and long term feedback responses to environmental conditions (e.g. Russell et al. 1970), is critical for managing natural resources and building societal resilience in the face of environmental change and climate variability (Turner et al. 2003).

Approach We will use a combination of land use change modeling, social survey techniques, and fine resolution remote sensing to develop spatial maps of how people influence the magnitude and distribution of water and nutrient transfers for historical, contemporary, and future times. An existing series of coarse historical land cover maps (21-category maps for 1971, 1985, 1991, 1999; (MassGIS 2010)) are the basis of our research that develops more detailed information about how suburban residents use their land. First, we will continue our mapping of the contemporary PIE study area at the 45-cm resolution, to produce a digital database of household, parcel-level patterns of lawns, other vegetation, and impervious cover not currently available. Preliminary results from these 45-cm resolution maps indicate that 25-30% of residential land is fine green vegetation, about half of which occurs on residential land, indicating the importance of further understanding non-residential manicured vegetation, such as golf courses (Figure 2.7). Second, we will continue using household survey techniques to understand social drivers of land use and land cover, including policy formation and implementation, lawn watering/fertilizing (e.g. Law et al. 2004, Vermuri et al. 2010, Guha 2009), domestic water use, vegetation composition, and views on various watershed issues (e.g. beaver expansion, low-flow water problems, willingness to support restoration, etc). Digital lawn data sets combined with surveys of lawn use will be used to refine estimates of anthropogenic cross-boundry N transfers. We will continue to survey towns in the Plum Island watersheds to update estimates of water and nutrient flows via public water supply and waste-water management (e.g. Figure 2.5, Claessens et al. 2006). These various forms of information will be incorporated into a stakeholder-driven scenario analysis of future land use and land cover, including spatial allocation, in order to determine the potential effectiveness of management alternatives (Figure 2.8) (e.g. Conway and Lathrop 2005). Spatially distributed data layers will be integrated with hydrological and biogeochemical process models (see 1B and 1C) to understand biogeophysical conditions throughout the basin over time and explore the impact of various management scenarios. We will document historical evidence of feedbacks within the PIE watersheds, especially with respect to water use (e.g. Polsky et al. 2009; Hill and Polsky 2005, 2007), and develop rule sets that can be incorporated into the network model (see 1B) to determine thresholds when human activity may be altered by biogeophysical condition.

Specific Research Question-Linkages 1B: *How do human activity and climate affect connectivity among watershed sub-ecosystems and how does this impact the watersheds overall ability to control the fluxes of water, organic matter and nutrients to the estuary?*

Connectivity among ecosystems is an important driver of ecosystem function characterized by threshold and non-linear behavior (Peters et al. 2004, 2008). Changes in connectivity impact the delivery of reactants and ecosystem function (Grimm et al. 2008), and therefore influence the watersheds capacity to respond to altered loads occurring due to elevated cross-boundary material transfers (see 1A). In urban watersheds, dramatic hydrologic and biogeochemical changes caused by impervious surfaces, water diversions, and pollutant loads alter land-water, upstream-downstream, and channel-floodplain connectivity (Poole 2002; Grimm et al. 2008), which together impact watershed-estuary connections. Climate variability and change interact with human activity to further influence connectivity (e.g. Wollheim et al. 2008).

Approach 1B. We will use a cross-scale analysis framework (Peters et al. 2008) to understand the impacts of changing connectivity in the heterogeneous Plum Island watersheds. We will 1) conduct targeted field sampling and experiments (synoptic surveys, flow path sampling, end member mixing analysis, storm event sampling, solute experiments) to quantify how terrestrial-aquatic, channel-hyporheic, and channel-floodplain biogeochemical connectivity is altered along gradients of human activity and consequences for material source and fate and dissolved oxygen concentrations (e.g. Christophersen and Hooper 1992, Pellerin et al. 2007, Chaves et al. 2008, Briggs et al. 2009; Figure 2.5); 2) continue our long-term monitoring of stream/river flow, suspended sediment, and chemistry in headwaters draining the three dominant land uses (urban, forest, wetland) and at the major basin mouths (Table 2.1) to document both long and short term patterns that would indicate changing connectivity (Peters et al. 2008); 3) further develop and apply existing process-based hydrology and biogeochemical models (e.g. Wisser et al. 2009, Wollheim et al. 2008, Stewart 2009) to quantify impacts of changing connectivity and geomorphic heterogeneity (see 1C; Fig. 2.9) at the basin scale, including future scenarios (see 1A). Modeling will integrate hydrologically-connected ecosystems in a river network context (Helton et al. in press). We will also integrate carbon dynamics into the network model to address coupled C and N dynamics. The new high-resolution, plot level data sets (see 1A) will also be used to increase the predictability of N loading from land to water.

Specific Research Question - Geomorphology: 1C) *How do changes in geomorphology throughout the river network (returning beaver, channel incision, dams, road culverts) affect the watershed-estuary linkage by altering the capacity of watershed ecosystems to mobilize and transform carbon and nutrients? How does geomorphology interact with current and future climate variability to control ecosystem processes and material fluxes to the estuary?*

Whereas connectivity defines whether materials are delivered to particular ecosystems, geomorphology influences ecosystem capacity to transform materials via its control on hydrologic residence times and reaction rates (Ocampo et al. 2006). Stream networks are increasingly viewed as dynamic “riverscapes” in which disturbances shape geomorphic structure and the arrangement of patches of stream habitat in time and space (Weins 2002, Benda et al. 2004). Humans shape the morphology within stream networks through a cascade of changes that include construction of mill dams (Walter and Merritts 2008) and flashier hydrographs and channel incision that are part of what has been termed the “urban stream syndrome” (Paul and Meyer 2001, Walsh et al. 2005, Wegner et al. 2009). In the Northeast US, extirpation and recolonization of beaver (Figure 2.10A) also shapes floodplains (Naiman et al. 1986, Busher and Lyons 1999). Accounting for geomorphic heterogeneity is necessary to assess whole river network capacity to influence nutrient fluxes (Fisher et al. 2007; Helton et al. in press). Geomorphological change in aquatic systems is also likely to be an important source of feedbacks to human decisions about stream management (such as the demand for river restoration), especially as urban populations increase, animal populations change and climate shifts (Goudie 2006, Chin 2006).

Approach 1C. We will use satellite and aerial imagery (including LIDAR), historical documents and field surveys to map how beavers, mill dams, road culverts and impervious surfaces have altered stream channel structure over time (Figure 2.10B). We will then link these geomorphic changes to stream hydrologic function and to biogeochemical transformations of N and organic matter by conducting targeted sampling of flowpaths and storm flows (Pellerin et al. 2008) in different geomorphic settings and by conducting stream solute tracing experiments (Thouin et al. 2009, Briggs et al. in press, Fig. 2.10C) across stream channel reaches with different geomorphic structure. The results from the stream network mapping and the flowpath and stream channel solute tracers will be used to parameterize the river network biogeochemical model to predict downstream material transport (see 1B above). With the model, we will assess how changes in geomorphic features impact material fluxes to the estuary under various climate and hydrologic conditions and compare that to our long-term data (Table 2.1).

For higher trophic levels, we will also assess how human-altered connectivity and changes in geomorphology within the stream network influence resident and anadromous fish populations and the historical and contemporary significance of fish as vectors of nutrient connectivity within the river network and from ocean to watershed (e.g. Post and Walters 2009) in collaboration with the higher trophic levels group (Q4C). For both anadromous and local fish, we will track the distribution, total numbers, timing of returns, combined with estimates of excretion rates, to test if fish, in fact, act as important transport vectors, especially in relation to the location of dams and other geomorphic blockages.

PROPOSED RESEARCH: MARSHES

QUESTION 2: Are the relative elevations of salt marshes at PIE in equilibrium with sea level and if not what are the consequences for primary production , biogeochemical cycling, and material exchanges between the marsh and estuary?

Rationale: The extensive marshes that we have today developed during the previous 4,000 years of relatively static sea level (Fig. 2.11) by prograding into bays and deltas (Redfield and Rubin 1962). Sea level began to rise beginning about 1700 and the rate now approaches about 3 mm/yr (Kemp et al. 2009), resulting in marsh transgression (Fig. 2.11). Plum Island marshes have begun to disintegrate over the past 50 years at the mouth of the estuary, due to a combination of lateral erosion and marsh ponding (Cavatorta et al. 2003), which we associate with the long-term increase in sea level and reduced sediment inputs. Reduced sediment inputs are the consequence of reforestation of the watershed following abandonment of agriculture in New England (Fig. 2.12). Consequently, the geomorphology of PIE marshes, including their relative elevation, should be changing in response to external forcing from the watershed (addressed in 1C) and sea level, but the speed at which the marsh can track changes in external forcing is unknown.

Morris et al. (2002) showed that the equilibrium states of a marsh, its relative elevation and its productivity, were dependent on the *rate* of sea-level rise. Marshes maintain equilibrium with rising sea level by accreting organic matter and trapping sediment. The sedimentation rate can be decomposed into several contributing processes. One is purely abiotic and results from the settling of suspended particles in proportion to the concentration of suspended particles, settling velocity, and the duration of flooding by tides. When present, vegetation enhances the deposition of sediment by sorbing suspended sediment directly onto leaf and stem surfaces, by reducing kinetic energy and increasing particle settling (Leonard and Luther 1995, Leonard and Croft 2006, Mudd et al. submitted), and by directly contributing organic matter to the soil (Darby and Turner, 2008, Turner et al. 2009).

The earlier model (Morris et al. 2002) has been updated to include organic matter accretion, suspended sediment concentration, and other variables, and was solved for parameters characteristic of Plum Island salt marshes to make predictions about how the equilibrium states of these marshes are evolving (Fig. 2.13). The standing biomass at equilibrium is completely defined by rates of sea-level rise ranging between 0 and 3 mm/yr (Fig. 2.13A). There is a tipping point near 3 mm/yr (Fig. 2.13B) beyond which the vegetated marsh will disappear. As the rate of sea-level rise approaches 3 mm/yr, close to the current rate (Fig. 2.13), the equilibrium depth of the marsh surface drops 1 m lower than the current marsh platform. Hence, the present marsh is predicted to be far from equilibrium.

Specific Research Question Geomorphology: 2A) *How will changing geomorphology and relative sea level affect the productivity of the marsh, the relative importance of primary producers, and overall primary production?*

As the marsh equilibrates at higher rates of sea-level rise, we expect that unit-area primary production and standing biomass will at first rise (Fig. 2.13A). This is consistent with bioassay results (Fig. 2.14A&B) and the response of primary production to positive anomalies in sea level (Morris, 2000, Fig. 2.14C). However, erosion of marsh creek banks will increase and the total area of marsh will decrease as creeks widen to accommodate a larger tidal prism. Consequently, the ratio of open-water:intertidal marsh will increase and areas of habitat supporting macrophytes and benthic and pelagic components of the systems will change. Marsh edge is also important habitat for secondary producers (Zimmerman et al. 2000, Minello and Rozas 2002), and since marsh disintegration results initially in an increase in total length of marsh edge, higher trophic levels should respond. This is addressed in Q4A. Creek banks also drain nutrient-rich, marsh porewater, and at PIE this has been estimated to be 160 m^3 $year^{-1}$ m^{-1} of channel length (Gardner and Gaines 2008), exceeding the discharge of freshwater into the entire PI estuary (347 x 10^6 m^3/yr, Vallino and Hopkinson 1998). This is significant because the concentrations of pore water nutrients (Fig. 2.15) are an order of magnitude greater than what we typically find in the open waters of PIE (http://ecosystems.mbl.edu /PIE/data/est/EST.htm). Drainage of NH_4, for example, could transfer 9x10^5 mol N annually to the creeks from the salt marshes. This too will affect the relative productivity of different sub-habitats, because rising sea level will increase the frequency of inundation of the high marsh and, hence, drainage (Wilson and Morris in prep).

A change in salinity gradient due to migration of salt water and rising sea level will also change the dynamics of nutrients and primary production in the system. In sharp contrast to the salt marshes, brackish water (*Typha*) marshes have low pore-water nutrient concentrations (Fig. 2.15) and probably function today as nutrient sinks. We expect that sinks will become sources as salinity rises. The effect of salinity on the biogeochemistry and benthic release of nutrients at PIE has been documented by earlier work (Bernhard et al. 2005, Giblin et al. 2009, Giblin et al. accepted, Weston et al. accepted). Thus, increased sea-level rise is likely to increase pore-water drainage, which is a significant source of inorganic and organic nutrients for the planktonic sub-system (Wright et al. 1987, Raymond and Hopkinson 2003). As transgression proceeds and relative marsh elevation declines, pore-water drainage of existing marshes should eventually diminish with the declining hydraulic gradient, while nutrient release from fresh and brackish marshes should increase as salinity rises.

Approach 2A: Long-term monitoring sites are located in 2 major marsh types where plant census and marsh elevation (Fig. 2.16) data are collected monthly during the growing season. A monthly census of plant populations (Morris and Haskin 1990, Morris 2007) is providing unparalleled temporal resolution of salt marsh production that is not corrupted by spatial variability. Bioassay experiments in progress are designed to measure growth responses of vegetation to relative marsh elevation (Morris 2007, Fig. 2.14A&B). Experimental plots also receive monthly factorial N and P additions to determine nutrient effects. Periodic surveys of ground transects and analyses of aerial imagery and LIDAR data (Morris et al. 2005) will be used to measure changes in plant community and marsh distributions. Integrated rates of marsh productivity will be contrasted with measurements of system metabolism as described in **3B**. 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 rates of migration of plant communities. Some of these will build 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 to provide local middle and high school students with opportunities to perform hands-on scientific research throughout the various ecosystems in the Plum Island Sound area. Various student activities, including monitoring the growth of *Phragmites* in salt marshes and effects of salinity on the growth of salt marsh vegetation are described on Mass. Audubon site http://www.massaudubon.org/saltmarsh/.

A series of ground water level recorders in *S. alterniflora* and *Typha* marshes are used to monitor the dynamic response of subsurface water in relation to tidal and climatic forcing. Characterization of marsh geomorphology and tidal creek drainage network configuration will be done using remote sensing and GIS technologies. Porewater samplers in 3 plant communities are used to monitor depth profiles (0-100 cm) and temporal changes in ground water nutrient concentrations (Fig. 2.15).

Specific Research Question: 2B) *Are PIE salt marshes transitioning from organogenic high marsh to minerogenic low marsh?*

One of the more provocative predictions from the modeling work (Morris et al. 2002) concerns the regulation of soil organic matter concentration. As the rate of sea-level rise increases and the relative elevation of the marsh surface decreases (Fig. 2.13B), the concentration of soil organic matter is predicted to decline (Fig. 2.13C). This occurs primarily because of change in the input of mineral sediment. At the highest elevation, which can only occur at the lowest rates of sea-level rise, access to mineral sediment suspended in flood water is limited, and belowground production and organic matter accretion alone are able to maintain elevation. As marsh elevation declines, mineral input increases, and as relative elevation drops below the optimum for vegetation, organic matter accretion decreases as well. This is consistent with what may be a trend at PIE of new low marsh dominated by *S. alterniflora* forming at elevations about 1 m lower than the current marsh platform. These new marshes are forming on a bed of mineral sediment along the margins of existing peat marshes or on bars in the channels. These marshes appear to be stable and expanding, and their sediments are mineral, not peat.

Yet the elevation of the *S. alterniflora* zone is apparently rising faster than sea level (Fig. 2.15), while the high marsh zone dominated by *S. patens* has risen at a rate of just 1.5 mm/yr. Mean tidal amplitude, which affects mean high-water level and hydroperiod, has decreased by about 5 cm during the last decade as a consequence of the lunar nodal cycle. The next decade should be dominated by an increase in tidal amplitude of the same magnitude and should give us a clearer idea of how the marsh responds to a rapid rise in sea level.

Approach 2B: Periodic surveys of ground transects, GPS surveys, and analyses of aerial imagery and LIDAR data will be used to measure changes in marsh distribution and elevation. End-of-season biomass harvests will document the relationship between biomass and relative elevation. Feldspar marker horizons (Cahoon and Turner 1989, Boumans and Day 1993, Cahoon et al. 2000) will be established in areas of newly formed marsh to measure sedimentation rate, and ceramic plates will be used to collect sediment. Sediment collections will be analyzed for organic matter content by weight loss upon ignition.

Specific Research Question Linkages: 2C) *What is the fate of the current standing stock of carbon?*

The age of the organic 'fines' in marsh sediment from depths between 0 and 70 cm varies from 2000-3000 yr (Wang 2008), suggesting that there is deposition of old, eroded carbon onto the surface. Close examination of marsh elevation data shows that the gains in elevation are discontinuous and occur during the winter. This is a characteristic of ice rafting (Wood et al. 1988, Argow et al. 2006), a process that deposits old sediment eroded from the vertical walls of marsh peat onto the modern surface. Hence, the marsh is cannibalizing itself; and this will affect the equilibrium of the marsh surface with sea level. In fact, ice rafting may account for the rapid rise in elevation of the *S. alterniflora* zone, which has been greater than the rate of sea-level rise (Fig. 2.16). The process of ice rafting, therefore, needs to be incorporated into the equilibrium marsh model. The fractions of eroded peat that are redeposited, mineralized, or exported as POC and DOC are unknown. This is important because DOC and POC export from the salt marshes may explain the net heterotrophy that has been observed in the lower estuary (Question 3B).

PIE interior marshes are also showing evidence of loss due to pond formation. Pond formation may be symptomatic of marsh disintegration or part of a dynamic succession (Redfield 1972). Some ponds are created by, and expand in size due to ice rafting, and eventually they connect and drain to creeks. This is followed by colonization by *S. alterniflora*, which may eventually return the marsh to its original elevation. Overall, however, accelerated sea level rise should decrease the spatial extent of marsh, decrease its relative elevation (Fig. 2.13B), and its sediment organic matter concentration (Fig. 2.13C).

Approach 2C: Change in total marsh area and carbon inventory will be documented using a combination of LIDAR data, coring, plot-scale elevation data, collections of sediment made on ceramic plates, and modeling. Sedimentation-Erosion Tables (SETs) and feldspar marker horizons (Cahoon and Turner 1989, Boumans and Day 1993, Cahoon et al. 2000) have been established at 12 sites across 3 major marsh types. Strategically placed ceramic plates collect sediment that will be analyzed for organic matter content by weight loss upon ignition. Carbon age will be determined by AMS ^{14}C analysis. The process of pond formation and development will be investigated using strategically placed SET stations, sedimentation plates, coring, and analysis of aerial imagery coupled with measurements of marsh metabolism as described in 3B. New to this proposal will be the installation of an eddy flux tower in the marsh to look at the carbon balance between the marsh, the atmosphere and loss to creeks (see 3B). The tower will be instrumented, maintained, and the data interpreted following an approach used in wetlands at FCE and VCR (Kathilankal et al. 2008) but using newer instrumentation. To the extent possible we intend to follow NEON protocols. We are exploring the control creek from the TIDES experiment as a possible location. Standing biomass (via a spectral radiometer), water level, net radiation, photosynthetically active radiation, air temperature and humidity will be simultaneously measured for input to a modeling study.

PROPOSED RESEARCH ESTUARY

Question 3- How do human activities and variations in climate that affect the coupling with watersheds, intertidal marshes and the ocean shape organic matter and nutrient transformations in estuarine tidal creeks and bays?

Rationale: Estuaries are among the ecosystems on Earth most subject to alteration by humans. Impacts are driven by activities on land that affect water and material inputs, by activities within the estuary that affect water circulation patterns and linkages with intertidal wetlands, and by changes in ocean systems that affect estuarine circulation and water levels. Some of the largest impacts from land result from human population growth and land use change, both of which are contributing to increased nutrient loading and reductions in organic matter inputs. Plum Island marshes are also changing as a result of sea level rise, which is contributing to increased flooding and greater exchange of materials between intertidal wetlands and tidal waters.

In the Estuarine Program area we will build on four major classes of activities that characterize our existing LTER effort in this focal area (monitoring, field and laboratory experiments, GIS, and integrative modeling). We will add new efforts to explore the effects of geomorphic pattern (marsh:water, edge length, relative marsh elevation, etc) on estuarine metabolism and benthic nutrient flux and to better understand the integrated marsh/estuarine C budget. Finally, we will examine the potential response of benthic filters feeders (clams) to variations in freshwater runoff and their potential to moderate predicted increases in N enrichment.

Specific Research Questions Geomorphology 3A. *How do variations in marsh / estuarine geomorphology affect patterns of metabolism and nutrient remineralization? How will changes in geomorphology that result from sea level rise and climate change affect estuarine metabolism and nutrient remineralization in the future?*

Evolution of the marsh-estuarine system in Plum Island reflects a dynamic balance between freshwater runoff and tidal mixing, sediment inputs and loss, sedimentation and erosion, and marsh plant stabilization of sediments, trapping of sediments and peat accumulation (Morris et al. 2002, Kirwan et al. 2008, Kirwan and Temmerman 2009, Mudd et al. 2009). Hydrologic gradients, and gradients in factors controlling sediment accretion along the length of the system translate into strong geomorphic patterns in the ratio of marsh to open water area, the ratio of intertidal flats to subtidal flats, the depth and frequency of intertidal marsh flooding, tidal creek drainage density, and length of creekbank edge. These geomorphic patterns are reflected in the distribution of salinity, marsh plants, marsh productivity, water residence time, volume of creekbank drainage, and benthic microalgal distribution and productivity. How these distributions interact to affect the spatial patterns of estuarine metabolism are unknown and will be a major new focus in our next funding cycle.

Approach 3A: *Estuarine system metabolism:* We will expand our existing network long-term core monitoring of YSI water quality permanent deployments to encompass sites of overlapping tidal excursion along the length of the Parker River - a length with the most extreme contrasts in geomorphic characteristics in this system. For example, marsh pannes and ponds are absent from the upper 10 km, but are major features from 10-15 km downstream. By "sampling" the YSI data record in salinity space (salinity is a tracer of water mass), we will construct measures of P, R and NEP along the geomorphic continuum. Statistical analysis of metabolic patterns will reveal the importance of the various geomorphic gradients we observe.

Modeling: We are continuing to develop our benthic biogeochemical submodel for inclusion in the general estuarine biogeochemistry model. Recent efforts have helped parameterize the role of salinity in determining ammonium release from subtidal sediments (Giblin et al. accepted, Weston et al. accepted) and in emergent marsh sediments (Giblin et al. unpublished). Over the next 6 years we will continue to focus on P, R, remineralization, and N cycling to further refine the model for the entire estuary. We will also collaborate with other Plum Island research partners (e.g., Sergio Fagherazzi and Matthew Kirwan) over the long term to aid in the development of a realistic estuarine geomorphic development / degradation model. Linking this new model to our coupled hydrodynamic-biogeochemical models will enable us to explore the ramifications of future changes in SLR, land use, and climate.

Specific Research Question Linkages 3B. - *How does the periodic flooding of intertidal marshes affect the primary metabolic pathways and C balance of estuarine and marsh subsystems?*

Early research that found little evidence of significant marsh grass grazing led to the hypothesis that excess organic matter produced in marshes was exported to adjacent tidal creeks and eventually the ocean where it supported a detrital-based foodweb and a rich, productive marine fishery (Odum 1961, 1968). Carbon mass balance budgets have suggested that upwards of 50% of above ground plant production had to be exported to tidal creeks to support measured levels of heterotrophy (e.g., (Wiegert et al. 1981 and Hopkinson 1988). Levels of net heterotrophy at PIE (Figure 2.17) suggest a strong dependence on allochthonous inputs from the watershed (Fig 2.18) and tidal marshes (Fig 2.19).

More recently Cai and co-workers (Cai et al. 1999; Cai et al. 2003; Wang and Cai 2004) offered a more unified concept of the estuary as a benthic subsystem consisting of vegetated marsh, intertidal mud flat and subtidal sediments coupled to an aquatic subsystem with associated planktonic and mobile fauna communities. While container incubations can be used to quantify metabolism of the aquatic subsystems, free water measures of dissolved O_2 and CO_2 within estuarine tidal creeks and bays integrate metabolism of both the aquatic and benthic subsystems. This was a significant new conceptualization of an estuary as it does not solely rely on physical transport of marsh organic C to tidal creeks to satisfy heterotrophic demands. Instead the water subsystem moves onto the marsh and there integrates some aspects of respiration either in the form of marsh microbes respiring CO_2 directly into the water, or DIC transported from marsh sediments into the overlying water. This may explain why component measures of water column and benthic respiration amount to only ½ that measured with free water techniques (e.g., Alderman et al. 1995.).

Approach 3B: *Flux studies:* We will address the “marsh effect” on whole water measures of system metabolism through the coupled flux tower / creekshed exchange experiment introduced in the Marsh Section (Q2C). To summarize, we will measure all forms of carbon exchange between the atmosphere and adjacent tidal creeks by instrumenting a small 1st or 2nd order tidal creekshed (Fig. 2.20). An eddy covariance flux tower will be sited in the creekshed so that its footprint closely matches creekshed boundaries. A sensor array in the tidal creeks will provide data on water and constituent flux to/from the creekshed. One element of the array will collect continuous measures of water level (to yield flux based on pre-established stage-discharge relations) and constituent concentrations at the tidal creek mouth. For CO_2 we will deploy a continuously recording SAMI CO_2 sensor. Sigma autosamplers will be used to collect water samples for later analysis of DIC, POC and DOC in the laboratory.

Importance of marsh macrophytes in supporting system heterotrophy: The fate of marsh grass NPP is still an open question. Our own tracer studies (^{13}C, ^{15}N, ^{34}S, ^{14}C), while useful in teasing out foodweb relationships, are equivocal in documenting the relative importance of marsh grass in supporting higher trophic levels and system metabolism (see e.g., Coffin et al. 1989; Peterson et al. 1994; Raymond and Hopkinson 2002). We propose to use stable isotope ratios of hydrogen (δD) to partition allochthonous and autochthonous organic matter sources, specifically algal, riverine, and marsh macrophytes. The utility of δD has long been recognized (Smith and Ziegler 1990) for distinguishing food sources in ecosystems (Smith and Epstein 1970, Macko et al. 1983), including streams (Doucett et al. 2007). Many of the challenges associated with the technique have been addressed with automated pyrolysis systems coupled to isotope-ratio mass spectrometers and by equilibrating all samples and calibration standards with local water vapor (Doucett et al. 2007). Deuterium will be analyzed in samples of potential plant sources, POC, and selected organisms representing various trophic levels (similar to Deegan and Garritt, 1997), but especially microbes which are responsible for 90% or more of total system metabolism (Hopkinson et al. 1989). Bacteria will be sampled through their bacterial lipids, which are typically depleted in deuterium. We will continue to sample C, N and S isotopes and follow them through the food webs (see Q4).

Other measures: We will continue our long-term core monitoring of water drainage volume from tidal creek banks. We will also conduct a series of incubation experiments to determine the lability of eroding marsh peat and its potential to sustain measured levels of system heterotrophy. Earlier isotopic studies showed an increased age of POC along the length of the estuary, which we attributed to eroding marsh banks. However there was little indication of an equivalent increase in the age of DOC or DIC, which we interpreted to signify peat recalcitrance. Incubation studies should help clarify these observations. Of particular interest is a better understanding of the conditions that favor peat decomposition since this may determine where in the estuary peat is more likely to decompose and where it will accumulate. Oscillating redox conditions (Aller 1994), a good supply of high quality electron acceptors and active benthic fauna have all been shown to speed decomposition rates. We intend to evaluate the effect of these factors by manipulating them in laboratory experiments.

Specific Research Question 3C) *What is the metabolic response of the estuary to short and long-term variations in watershed runoff, sea level rise, and climate change? How do variations in salinity affect benthic remineralization and the distribution of clams and their role in ecosystem dynamics? How do the distribution, biomass, and filtration efficiency of clams affect rates of benthic metabolism and how do variations in watershed runoff interact with clams to control eutrophication?*

We have documented profound changes in land use and the hydrologic cycle in the Ipswich and Parker River watersheds (e.g., Claessens et al. 2006) and predicted substantial changes in N and water runoff in the future in conjunction with urbanization. We have also documented the rate of sea level rise in the estuary (2.5 – 3 mm/yr since the 30's), and rates are predicted to increase substantially over the next 100 yrs due to global warming. With land use and climate change altering water and nutrient inputs and SLR altering marsh geomorphology, we can expect concomitant changes in estuarine system community structure, metabolism, and nutrient cycling. Clams (*Mya arenaria*), which comprise an important fishery in Plum Island Sound, are known to be effective moderators of eutrophication through their efficient filtration of phytoplankton. Clams also greatly alter N and P cycling. Presently clams are limited to the lower ½ of the estuary because of salinity distribution and thus play no role in moderating the algal blooms experienced in the upper estuary. A management-relevant question is whether declining freshwater discharge will shift clam habitat upstream, thereby positioning clams to intercept the blooms and mediate eutrophication. Salinity distribution also plays an important role in N cycling (Giblin et al. accepted), affecting the timing and magnitude of NH_4^+ flux to overlying water, and the balance between denitrification and dissimilatory nitrate reduction (DNRA). The net effect of DNRA appears to be N conservation, which we fear will further exacerbate eutrophication potential at PIE.

Approach 3C: *Monitoring:* We will continue long-term core monitoring of planktonic community structure (CHEMTAX), algal biomass (chl *a*), nutrient concentrations, metabolism, and benthic nutrient flux through our semi-annual monitoring and continuous YSI deployments. In this funding cycle will extend these surveys to tidal Ipswich River portion of the estuary. In contrast to the estuarine region that is strongly affected by the Parker River, the region affected by the Ipswich experiences 10x greater runoff, but average freshwater residence time is 10x shorter.
Clams: New effort will focus on quantifying the distribution of clam biomass and its relation to salinity, the metabolism and filtration efficiency of clams, and clam harvest. We currently have a single site where we measure benthic fluxes in clam flats and these measurements will be expanded. *Modeling:* We will add a clam component to the benthic submodel (described above) to explore the potential for clams to control eutrophication in the future.
Effect of salinity variations: During PIE I and II we gained a great understanding of the effects of varying salinity on benthic N cycling, especially NH_4^+ flux and denitrification, in subtidal sediments (Giblin et al. accepted and Weston et al. accepted). We will add new efforts in PIE III to examine the effects of nitrate concentration and salinity on DNRA and its relative importance in N cycling. We will continue using laboratory core manipulations and incubations and take advantage of natural gradients in nitrate concentration, organic matter types, and salinity around the Plum Island estuary to address this question.

HIGHER TROPIC LEVEL

Q4. What are the consequences of changes in ecosystem spatial configuration and dynamics for the structure and transfer of productivity in food webs, and the function of higher trophic levels in estuarine ecosystems?

Rationale: Secondary production, especially top predators, is strongly influenced by the interactions between an ecosystem's internal food web structure and connectivity (the fluxes of energy and matter through species and habitats) and the connectivity among habitats (the influx and export of organisms, energy, nutrients among habitats and ecosystems) (Fig. 2.21, Deegan et al. 2000, Chesney et al. 2000, Deegan 2002, Deegan et al. 2002, Kneib 2000, 2003, Gillanders et al. 2003, Deegan and Buchsbaum 2005; Nagelkerken 2009). For example, the annual variation in the 2% bottom salinity location, controlled by the interplay of river and tidal fluxes, has a significant relationship with many important processes, including the supply of plankton, fish survival and the relative abundance of planktivorous, benthivorous and piscivorous fish (Jassby et al. 1995, North and Houde 2003). Our understanding of controls on the transfer of productivity to mobile predators, such as striped bass and birds that move among and integrate larger and more complex habitat landscapes, is less well developed than that of within-habitat controls for invertebrates and small forage fish species (Simenstad et al. 2000). Understanding how river, marsh, open bay areas are linked by and differ in their support of biota and how food webs change with watershed influences, climate and geomorphology is key to the long-term sustainability of higher trophic levels in coastal regions (Fig. 2.21).

With our prior LTER work, we have developed a good understanding of sources organic matter, controls on and pathways of benthic and pelagic energy flow and top down controls in marsh food webs that advance our understanding of internal structure and connectivity. We found through isotopic surveys (Fig. 2.22), experimental manipulations (detrital removal, nutrient additions) and ^{15}N additions in marshes and rivers that food webs were supported predominantly by local primary production (Deegan and Garritt 1997, Hughes et al. 2000, Buchsbaum et al. 2009, Galván et al. 2008). Some species responded to changes in organic matter availability by altering their behavior or position in the food web (Buchsbaum et al. 2009, Galván 2008, Galván et al. submitted), resulting in substantially different food webs (Johnson et al. 2009). We found that although striped bass move throughout the estuary, individuals establish central feeding areas (Fig 2.23; Mather et al. 2009, Pautzke et al. 2010,) with residents in shallow tidal rivers more dependent on benthic/marsh food webs than bass in the deeper open bay (Walter et al. 2003, Ferry 2003). Stable isotopes provide a synoptic method for tracking benthic or pelagic production through food webs (Pruell et al. 2003, Fry et al. 2008, Galván et al. 2008). We are now well positioned to look at what intrahabitat geomorphic attributes (edge, flooding, water depth) and land scale features (habitat linkages, configurations, locations) influence efficient transfer of production through food webs to top consumers.

Our new research focuses on: **Q4A)** the influence of the changing geomorphic setting and hydrologic regime in creating hot spots of secondary production, **Q4B)** the interplay between biota and ecosystem function, and **Q4C)** the linkage by motile organisms across multiple habitats and estuaries. We use the same conceptually approach in freshwater (presented in the Watersheds section) and estuarine areas, and examine linkages between these two parts of the coastal system by motile organisms. We use a combination of surveys of fish and bird communities across different habitats and process measurements on model organisms: 1) mummichog (fish, *Fundulus*) and 2) grass shrimp (*Paleomonetes* sp.) as a key small nekton in marsh and benthic food webs, 3) Atlantic silversides, a small fish of open bay, pelagic food webs, 4) sand shrimp (*Crangon* sp), open bay, benthic food webs, 5) softshell clam (*Mya*), a filter feeder associated with open water intertidal areas and an important fishery 6) river herring, anadromous species that integrate across fresh, estuarine and ocean,7) striped bass (*Morone* sp.), an iconic top predator and an important fishery species and 8) add new work on waders and shorebirds.

Specific Research Question Geomorphology 4A: *What are the configurations of habitats, hydrodynamics, and geomorphic features (bathymetry, edge, etc.) that create regions of high secondary production and efficient energy transfer to higher trophic levels?*

The mosaic of geomorphology, habitats, and hydrodynamics combine to influence the location and the amount and kind of secondary production in estuaries. Differences in geomorphology, such as elevation that determines the amount of flooded marsh, are known to be important in determining salt marshes production of small forage nekton species, such as fish and shrimp (Javonillo et al. 1997, Halpin 2000, Teo and Able 2003, Craig et al. 2006). Despite this, there is a surprising level of uncertainty about how key attributes influence transfer of productivity in a food web. For example, one study showed that increased geomorphic complexity, such as a greater marsh to edge ratio, increased nekton (shrimp) abundance (Haas et al. 2004), but other work found lower nekton (mummichog) growth rates in more complex habitats (Kneib 2009). In PIE, we found highest nekton (mummichog) growth rates in brackish marshes, which flooded more frequently, compared to salt marshes (Fig. 2.24, Haas et. al 2009).

We have shown that mobile fish predators (striped bass) tend to concentrate (Fig. 2.23, Pautzke et al. 2010) in specific areas but we do not fully understand what combination of geomorphology, hydrodynamics and prey production creates these feeding hotspots. We hypothesize that long-term changes in geomorphology and hydrology will alter benthic/marsh and pelagic food webs, with different implications for fish and bird predators. Striped bass (preferring deep water and pelagic fish production) are favored by current conditions, while the projected expansion of marsh ponds, tidal flats and benthic production favors waders and shorebirds. We know little about the global declining populations of waders and shorebirds, although PIE is an internationally protected shorebird stopover area (NBCI 2009). Birds can consume as much as 40% of benthic invertebrate production (Mendonca et al. 2007, Kuwae et al. 2008), potentially altering tide flats (Bouma et al. 2009).

Approach: 4A) 1*)*To understand changes in organic matter source and benthic/pelagic food webs we will continue our "core" ^{13}C and ^{15}Nisotopic survey of 10 key functional groups (Fig. 2.22) adding striped bass as an integrating top predator. We will also begin new analyses of hydrogen isotopes (δD) to differentiate saltmarsh and riverine inputs (See Estuary section for δD explanation). We will relate isotopic changes to trends such as increased marsh flooding with sea level rise, extreme weather events such as droughts and floods, and long-term changes in the ratio of marsh to open water. Long-term observations of isotopic values may indicate shifts in ecological conditions and pathways of energy flow (Pruell et al. 2003, Fry et al. 2008). *2*)To detect responses of small forage nekton (small fish, crabs and nekton) to changing conditions, we will continue our core long-term measurements of the general abundance of small forage species (<10 cm fish, shrimp and crabs using seines and trawls), but we will change methods of assessment. We have found that the variability associated with tide height at time of sampling produces an unacceptably high variation in the seine survey data (Haas, postdoctoral analysis, pers. com.), therefore we will switch to using flume measurements conducted on spring high tides (Deegan et al. 2007) after conducting contemporaneous seine surveys to inter-calibrate these approaches. We have several years of flume net data (2003-2007, 2009-2010) as part of the TIDE project that will form a baseline. Developing this protocol will be part of the HTL postdoc in 2010 – 2011. *3)* To determine the influence of changes in marsh geomorphology and flooding regime (see Marsh section), we will couple the new measurements of abundance (flume nets) with growth (length-frequency and RNA:DNA analysis, Buckley, L. et al. 1999, Chícharo and Chícharo 2008, Stierhoff et al. 2009) of key species (*Fundulus, Menidia, Paleomonetes, Crangon*) in brackish to saline marshes and relate these to marsh habitat complexity (GIS; marsh edge ratio, etc. Whaley et al. 2007), flooding (VFCOM hydrodynamic model) and organic matter source (isotopes) and diet. *3)* To determine the combinations of geomorphic features (tidal creek confluences or complex bathymetry) and hydrodynamic features (current profiles, eddies, temperature, salinity, depth) that concentrate top predators and maximize foraging return, we will use new fine-scale positioning acoustic tag technology (VEMCO) to measure the movement and foraging locations of striped bass and couple this with measures of diet (type and quantity of prey) and growth (RNA:DNA ratio). *4)* We will identify waders and shorebirds use of specific locations (tidal flat, marsh surface, open water at high and low tides) by twice monthly censuses and activity observations (feeding, loafing etc.). This will augment the large dataset of bird counts regularly collected by the Parker River National Wildlife Refuge (Fig. 2.25). We predict that projected increases in marsh ponds will favor waders, while increases in intertidal flats will favor shorebirds, relative to global trends. We will correlate avian parameters with sediment, geomorphic and landscape (GIS, Lidar) characteristics (Gawlik 2002, Granadeiro et al. 2003, Trocki and Paton 2006, Raposa et al. 2009) and global trends (Calvert et al. 2009, see Q4C below). ***Modeling* –** The long-term changes in population size, distribution and isotopic composition of organisms will be coupled with spatially explicit habitat suitability, behavior (See Q4B) and hydrodynamic models to develop relationships among changes in water flux (fresh and salt), sources of primary production, changes in ecosystem geomorphology and production of higher trophic levels.

Question 4B*: How will the changing distribution and abundances of higher trophic levels influence ecosystem dynamics?*

There is now consensus that species composition and behavior, including that of top consumers, play an important role in regulating food web structure and ecosystem processes (Worm et al. 2000, Naeem 2002, Heithaus et al. 2008, Feld et al. 2010) and are more important in estuaries than previously thought (Heck & Valentine 2007; Deegan et al. 2007, Fleeger et al. 2008, Johnson and Jessen 2008, Sala et al. 2008, Bertness et al. 2009). Our TIDE marsh experiment demonstrated that that the functional role of mummichogs varied over the landscape, ranging from strong top down control on marsh detritivores to weak interactors and herbivores in creeks (Fleeger et al. 2008, Johnson et al. 2009). Our finding of distinct individual striped bass foraging areas (Fig. 2.23) combined with specialized feeding (Walter et al. 2003) suggests that individuals become more efficient predators by remaining in specific areas, maximizing their growth and potentially exerting top-down control on prey. Coast wide our understanding of the potential ecosystem functions of striped bass is limited as most work was done when striped bass were 1/10th of their current abundance (Hartman 2003, Worm et al. 2003). The recovery of striped bass (http://www.nefsc.noaa.gov /sos/spsyn/af/sbass/) provides a unique opportunity to understand the role of a mobile top predator in estuarine dynamics.

Approach: 1) To measure the effects of reduced fish abundance, we will continue our long-term tidal marsh experiment (TIDE, see Integrating Experiments section). We will test whether the observed increase in detritivore abundance (Johnson et al. 2009) alters litter decomposition or bird foraging (Johnson et al. 2009) across a nutrient-loading gradient. 2) To determine the potential for top-down control by striped bass, we will couple our measurements of striped bass feeding location and intensity with measures of prey available (forage species surveys) in specific areas and long-term data on forage species will be correlated with striped bass recovery. *3)* To understand how changing tidal flat distribution and position in the landscape will affect the clam production and nutrient cycling, we will survey intertidal areas for clam abundance and correlate this with intertidal flat characteristics (spatial location, sediment, elevation, salinity regime) and nutrient cycling (see Estuary section). ***Modeling-*** Ongoing development of an integrated food web model will be used to evaluate the role of mummichog in salt marsh function and behavioral modeling will be used to understand the potential foraging impacts of striped bass (Fig. 2.26, Finn, Mather and Deegan, in prep.)

Specific Research Question – Linkages 4C: *How will linkages mediated by motile organisms be altered by changing spatial and temporal ecosystem dynamics?*

An important characteristic of many higher trophic level species is their degree of mobility and movement among habitats and ecosystems (e.g., Kneib 1997, Deegan et al. 2000, Gillanders et al. 2003, Ramenofsky and Wingfield 2007, Mather et al. 2010). Both large and small-scale animal movements have long been recognized as avenues through which trophic impacts can be dissipated, neutralized, or intensified (Hilborn & Mangel 1997; DeAngelis & Petersen 2001). In additions to important within watershed movements, both birds and fish have migratory connections to distant ecosystems that may influence their abundance and thus function in PIE. The global abundance of shorebirds is closely associated with continental-scale population changes occurring in breeding and wintering locations (NBCI 2009). We found that 2/3^{rds} of the PIE summer resident striped bass spent the winter in Delaware Bay (Mather et al. 2010), suggesting a strong specific connection between feeding and overwintering/ spawning estuaries. Delaware River basin striped bass age-0 recruitment in 2003 was at least five times higher than in the 1980s (ASMFC 2004) suggesting PIE might experience an increase in striped bass 5 to 7 years later. Understanding the specificity of movement of organisms within and between ecosystems, and the implications of limits to populations imposed by conditions in distant ecosystems, is key to predicting both their impacts on estuarine processes and their response to local and global climate change.

Approach 4C: *1)* To understand food web links between marshes and open bay areas via forage species migration, we will estimate the flux of energy and materials via small fish and shrimp (e.g., Deegan 1993) using the flume net and growth work. *2)* To understand the role of anadromous fish, we will monitor river herring migration and distribution between and within estuaries and rivers (See Watersheds section 1C). *3)* To begin to understand the influence of overwintering conditions on summer feeding estuaries (e.g., Reinert and Peterson 2008), we will determine the striped bass migration to wintering estuaries using an acoustic tag detection array in place along the Atlantic coast (Mather et al. 2010 in revision). *4)* To determine whether use by shorebirds and waders is a reflection of local conditions or global trends, we will relate these abundances to local changes (see Q4Babove) and breeding area success (NBCI 2009). ***Modeling:*** To determine if individual striped bass foraging movements across habitat patches of different foraging profitability intensifies and dissipates their trophic impact, we will use a dynamic behavior model (Fig. 2.26, Finn, Mather and Deegan, in prep.), which predicts the consequences of movement for consumption and growth.

MODELING AND SYNTHESIS

The objectives of the Modeling and Synthesis component of the PIE-LTER program include 1) interpolation and extrapolation of limited field observations across the entire PIE domain, 2) quantitative testing of hypotheses and development of new theoretical models, 3) understanding whole system response to external forcing and internal dynamics, and 4) forecasting and scenario generation of PIE responses to global change and human induced alterations, both planned and unintended. Modeling allows us to examine the strength and directionality of linkages between subsystems that is necessary to understand response of the Plum Island Ecosystems to internal dynamics and external drivers and human activities. Organizationally, our modeling effort is subdivide into two main location-based areas: I. Watershed, consisting of uplands and river networks; II. Estuary, consisting of water column, marsh, intertidal mudflats and benthos. Within each research area, modeling thrusts focus on transport processes, alterations in geomorphology, and biogeochemistry/food web processes.

Watershed Modeling: Originally we used HSPF (Bicknell *et al.* 1997) to model both watershed hydrology and biogeochemistry (Filoso *et al.* 2004, Zarriello and Ries III 2000); however, we have found this model to be over parameterized, so have discontinued its use. Recently we developed a river network model to explore how hydrologic conditions, biogeochemical activity, and increased loading influence nutrient exports from the watersheds (Wollheim et al. 2008, Stewart 2009). The model is spatially distributed at 120 m grid cell resolution. It is designed to implement a water balance model (Wisser et al. 2009) modified to account for impervious surfaces (e.g. Pellerin et al. 2008) to generate runoff, which is then routed downstream to generate spatially distributed discharge. Channel dimensions (depth, width, velocity) vary over space and time according to at-a-site and downstream power law relationships as a function of discharge (Leopold *et al.* 1964, Park 1977). Biogeochemical processes are implemented based on empirical findings (e.g. Mulholland *et al.* 2008 for denitrification). Recent advances have incorporated both surface and subsurface transient storage dynamics (Stewart 2009) to distinguish the role of different sub-systems of stream channels (Fig. 2.27). We will enhance the model by accounting for connectivity with other subsystems (floodplains) and geomorphic heterogeneity. We will use the transient storage module as the basis for incorporating the role of floodplain activity. The transient storage module will account for exchange rates to and residence times on floodplains (i.e. surface transient storage), that vary depending on discharge, which is impacted by multiple human activities. We will also improve the model to account for geomorphic heterogeneity, including lakes, beaver ponds, and reservoirs to test the impact of changing geomorphology on nutrient fluxes. Hydraulic and biogeochemical parameters for different sub systems will be determined using field measurements, remote sensing, and experiments that are used in Question 1. The model will then be integrated with the land use change models (Question 1) to explore how human activities are altering flux of materials to the estuary, and the role that changing connectivity and geomorphology are having on these fluxes. We will also begin integration of this new watershed model with our estuarine model, described below, so that we can understand how perturbations propagate through the entire land margin ecosystem, which will be integrated with social feedbacks.

Estuarine Modeling: We have developed 1D, 2D and now 3D hydrodynamic models for PIE estuaries. Our current focus, which will extend into the next funding cycle, is on development PIE-FVCOM, which is based on UMass Dartmouth's 3D Finite-Volume Coastal Ocean Model (FVCOM: Chen *et al.* 2003, Chen *et al.* 2004). Recently, 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 R. to the southern entrance of PI Sound (Fig. 2.28). PIE LIDAR data combined with GPS-based depth soundings have been used to construct a high accuracy marsh topography-bathymetry model (Fig. 2.29). We have found that the northern PI Sound connection with the Merrimack River results in an injection of freshwater into the northern marshes via PI River during flood tides (Fig. 2.30), and asynchrony in tidal forcing at the two mouths produces a clockwise residual current between PI Sound and the Merrimack River (Fig. 2.31) (Zhao *et al.* 2009). While initial ADCP and CTD surveys support the influence of the Merrimack R. on PI Sound circulation, we are planning more detailed surveys to confirm the residual circulation pattern. The model also predicts that the marsh platform alters tidal harmonics such that water holdup within the system occurs with a 3 day periodicity, which we plan on experimentally verifying by collecting several months of high accuracy tidal elevation data in the Sound and Merrimack River.

Our new high resolution 3D model allows us to examine hydrodynamic flow fields at specific locations within PIE estuaries that correspond to areas of interest to higher trophic levels (Question 4). As explained in the Higher Trophic Levels (HTL) Section, acoustic tags will provide striped bass location information as a function of time which can then be compared to flow fields that exist at the same location. By correlating striped bass presence to flow field characteristics, such as flow velocity, vorticity and shear (Fig. 2.32), we will be able to identify hydrodynamic associated rules that can be used in the individual-based modeling that is being developed for HTL. To facilitate habitat mapping, we plan to improve our bathymetry model using water-penetrating LIDAR (Vierling *et al.* 2008). FVCOM hydrodynamic model output will also facilitate advancement of our marsh accretion/loss model being develop in the Marshes Research Group (Question 3). Currently, the marsh accretion/loss model is under theoretical development (Morris 2007), but once completed, we can use the theory to predict marsh loss or accretion, which will be used to alter marsh elevation in the current marsh topography-bathymetry model. Using an iterative approach, PIE-FVCOM will be run with the altered marsh topography, which will result in new flow fields that will be fed into the marsh accretion/loss model. By combining the two models we will be able to examine how marsh geomorphology may change over time as well as test hypotheses regarding marsh development under altered nutrient loading. With the new watershed model, we will also explore how alterations in stream geomorphology changes watershed sediment export that feeds marsh formation.

Biogeochemistry modeling: The above 1D, 2D and 3D transport models are used to drive our constituent transport and reaction models that predict estuarine biogeochemistry and food web dynamics. We plan to advance an existing biogeochemistry model as well as develop a new model during this funding cycle. Because PIE estuaries host a large shellfishery and the water column is vertically well mixed (Vallino and Hopkinson 1998), filter feeding organisms should play an important part in the PIE estuary (Strayer *et al.* 1999, Hily 1991); however, to date we have only crudely modeled their impact (Hopkinson and Vallino 1995). Consequently we plan to explicitly incorporate a shellfish functional group in our compartment-type models (Hopkinson and Vallino 1995, Vallino 2000, Wan and Vallino 2005). Our model will be based on existing shellfish models (Dowd 2005, Hoffman *et al.* 2006, Ren *et al.* 2010), but we will begin developing the compartment model to operate with PIE-FVCOM, which has no PIE-based biogeochemistry models yet. Because FVCOM is widely used in the oceanographic community, our biogeochemical models will have potential wide use.

The second type of model we will begin developing is a Darwinian-type selection-based model (Follows *et al.* 2007) that has several advantages. In this type of modeling, a population of organisms is modeled that differ only in trait attributes, such as optimal temperature, salinity or light level for growth. The organisms then compete within the modeled space (PIE-FVCOM domain), under Darwinian selection pressure. Those "species" with the optimal attributes for a given habitat come to dominate locally. Once the model comes to pseudo-steady state, survivor attributes can be examined and compared to field observations to determine if the modeled attributes are truly important. The main advantage of selection-based models is that community structure is allowed to adjust as environmental conditions change or as different habits become available; an important characteristic not shared with conventional compartment-type models (Vallino 2000). Our initial modeling effort will focus on phytoplankton that can be compared to our chemtax field observations that produces species-level information. Once demonstrated, we will then expand the model to incorporate higher trophic levels.

Theoretical Modeling: In addition to models that complement our field and experimental-based research, we are also using models to advance new theories on the controls of biogeochemical processes. In this research, we model ecosystem biogeochemistry as a metabolic network where function is distributed across different organisms (Vallino *et al.* 1996, Vallino 2003). In ecosystems, expression of particular pathways in the distributed metabolic network (Fig. 2.33) depends on the relative abundances of organisms in the community; however, organisms are not specifically modeled. Instead, the ecosystem is viewed as being comprised of biological structure, $\mathfrak{S}$, that is allocated to those pathways based on some optimal criteria that living systems follow, subject to resource and known conservation constraints. Recently, we have been investigating if the principle of maximum entropy production (MEP) (Dewar 2003, Dewar 2005, Niven 2009) can be used as the optimization criterion. Basically, the MEP principle states that non equilibrium systems will organize so as to maximize the rate of entropy production, which is equivalent to maximizing energy dissipation rate (Schneider and Kay 1994). The theory has found wide application (Christen 2006, Chung and Vaidya 2008, Hill 1990, Jenkins and Inman 2006, Kleidon and Lorenz 2005, Paltridge 1975, Wang *et al.* 2007), and because MEP is based on well established thermodynamics, we have found it to be readily applicable to metabolic network representations of biogeochemical processes (Vallino 2009). We plan to extend our zero-dimensional MEP-based metabolic model to 3D (Fig. 2.34), so that it can be incorporated in our FVCOM simulations. We can then compare biogeochemical predictions based on MEP to predictions from more conventional approaches we are also developing. If MEP is a fundamental property of nonequilibrium processes as currently proposed, then we believe models based on MEP should exhibit greater prediction skill than conventional models when calibration data is not available. We will conduct model comparisons under various extrapolations to determine the validity of the MEP-based approach.

RESPONSE TO 3-YR REVIEW

Our review team felt the PIE team had made excellent progress in individual research areas. Both external review team and the letter from the program offices pointed out the importance of synthesis activities at this stage. The review team recommended that we "*start designing, testing and programming* for a broader synthesis that stretched across research areas. A related comment was that *"an apparent mismatch between the original PIE framework and the evolving program is exemplified in the apparent, but understated exploration of contemporary ecological theory*. The program offices encouraged us to "*consider expanding synthesis activities with the other coastal LTERs*". In the last three years we have moved toward all these goals. First, by reorienting our questions toward examining linkages and feedback and by incorporating the unifying theme of geomorphic change between the groups. The theory of "ecomorphology" is still evolving (for example see Stallins 2006; Fisher et al. 2007) but there is a growing appreciation for the need to understand the feedbacks between "form and function". Second, by working actively with the other coastal LTERs to generate compatible data sets and experiments we are creating opportunities to synthesize long-term data. Third, by jointly writing synthetic articles and exploring new funding opportunities with other coastal LTERs and coastal investigators. Finally, by beginning to synthesize our current knowledge in an LTER synthesis volume. Our plan would be to have the outline by the three-year review and the draft book by the end of the next funding cycle.

One of the other comments from the review team was that *"opportunities remain for gaining information about the role and importance of higher trophic levels in overall system dynamics"*. To address this we have strengthened this area by including Dr. Mather in the budget, and by looking at the role of some key species, such as bivalves, in system dynamics.

The review team was supportive of our inclusion of social science in our research and we have further strengthened this aspect of our program by bringing in Colin Polsky, who has been collaborating with us for the past 5 years through supplements and outside grants, as a full research partner.

SIGNIFICANCE OF PROPOSED RESEARCH

Coastal ecosystems are experiencing changes in watershed inputs, climate, and sea level, and in many cases, at unprecedented rates. Our ability to generalize on the consequence of these changes to coastal ecosystems is still primitive, in part due to the tremendous spatial and temporal variability in the physical , chemical and biological components of these ecosystems. The research outlined in this proposal will contribute to a better understanding of how coastal ecosystems respond to changes in drivers. Our increased emphasis on linkages and feedbacks will allow us take the next steps need to predict the long term trajectory that these systems will follow as drivers change. Our increased emphasis on the role of geomorphology and "ecogeomorphic" change will allow us to move beyond static system templates and explicitly model spatial and temporal variability and see how it changes in response to outside forcing. Finally, by beginning to incorporate human actions and feedbacks we are now capturing one of the key components of change for most coastal systems and moving PIE into the ISSE framework.

We also believe our work will contribute to a broader understanding of the responses of ecosystems to global change. Many of the issues we are examining, the prorogation of disturbance across the landscape, the importance of biotic controls relative to abiotic, and the importances of feedbacks between "form and function" are key questions in ecosystems ecology.

We believe we have identified key research areas that will greatly advance our understanding of how external drivers, ecosystem dynamics, and human activities interact to shape organic matter and nutrient transformations in linked watershed and coastal ecosystems. We have outlined a very ambitious research agenda for the next six years. We realize that to accomplish them we will need to continue to attract outside funds and form strong scientific, educational and outreach partnerships as we have in the past.

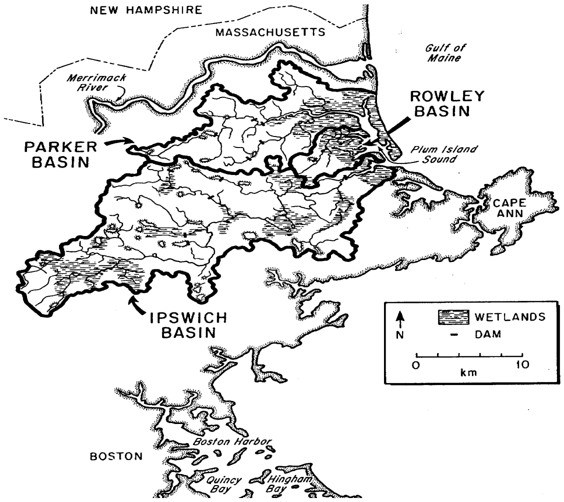


Figure 2.1. The Plum Island Ecosystem LTER which includes the watersheds of the Parker, Rowley and Ipswich rivers, their estuaries and tidal marshes, and Plum Island Sound. The Sound connects to the Gulf of Maine.

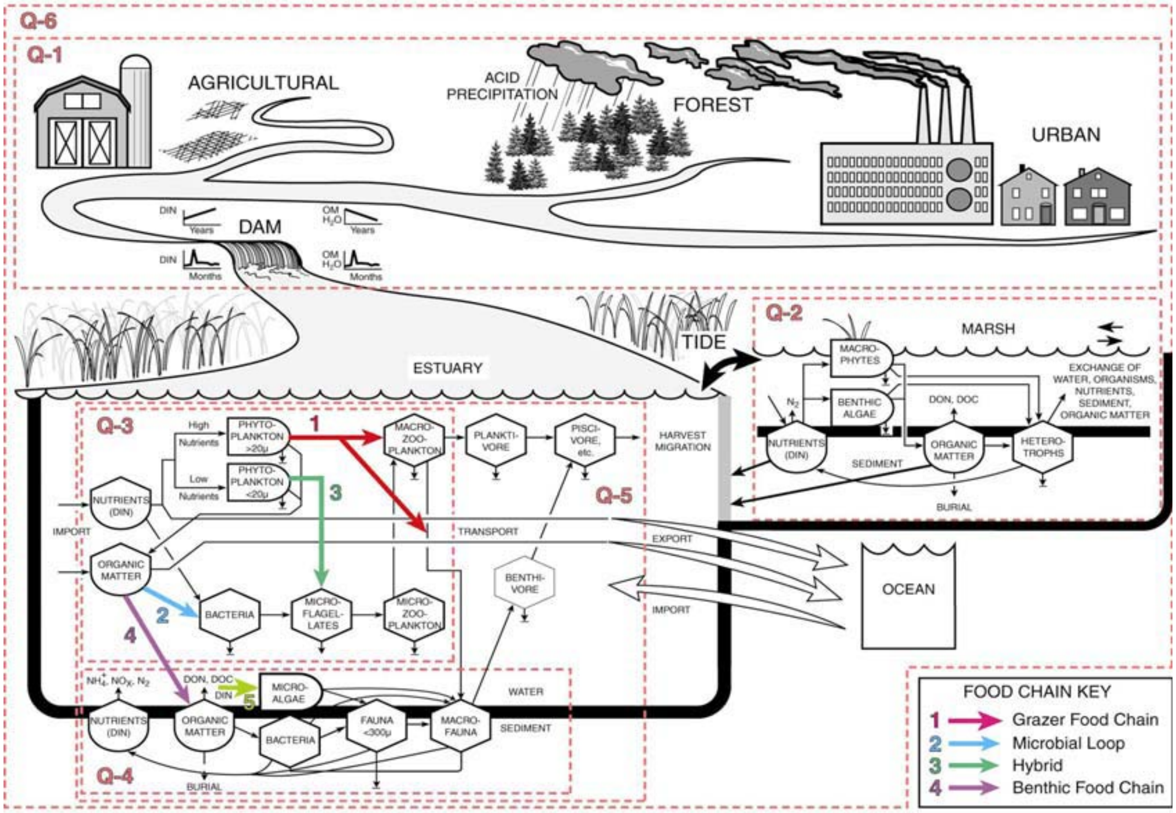


Figure 2.2. Our conceptual diagram of the PIE-LTER linked ecosystems that formed the basis for the PIE-I and PIE-II and also defined our programmatic areas. The diagram reflects the strong focus of our first proposal on the biological and physical transformations of organic matter and inorganic nitrogen from watersheds (Q1) and marshes (Q2). These inputs are processed by organisms in the marsh (Q2), estuarine water column (Q3) and subtidal benthos (Q4). Large mobile organisms in higher trophic levels move between compartments (Q5). Synthesis across program areas was achieved though integrating experiments and modeling (Q6). With this proposal we will be merging benthos with estuarine water column to form one estuary program area.

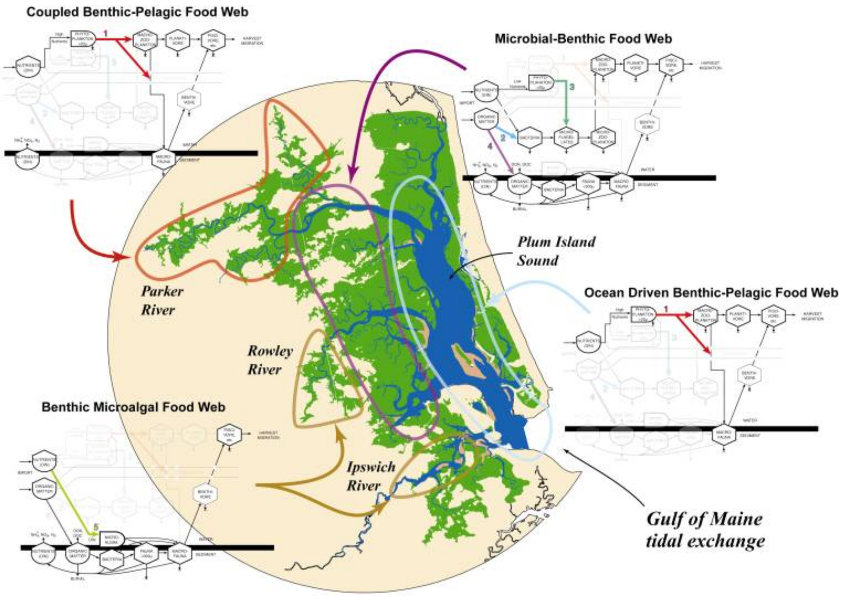


Figure 2.3. Spatial variations in food webs in the PIE-LTER. External drivers, especially water residence time, were conceptualized to define a geomorphic or hydrologic template upon which the effects of DIN and organic matter inputs on foodweb structure operated. The diagram shows four foodweb structures that develop in areas that differ in hydrodynamics and loading. In this proposal we expand this concept by acknowledging that the geomorphic setting is not a static "template" but may change over time due to changes in drivers and through internal feedbacks.

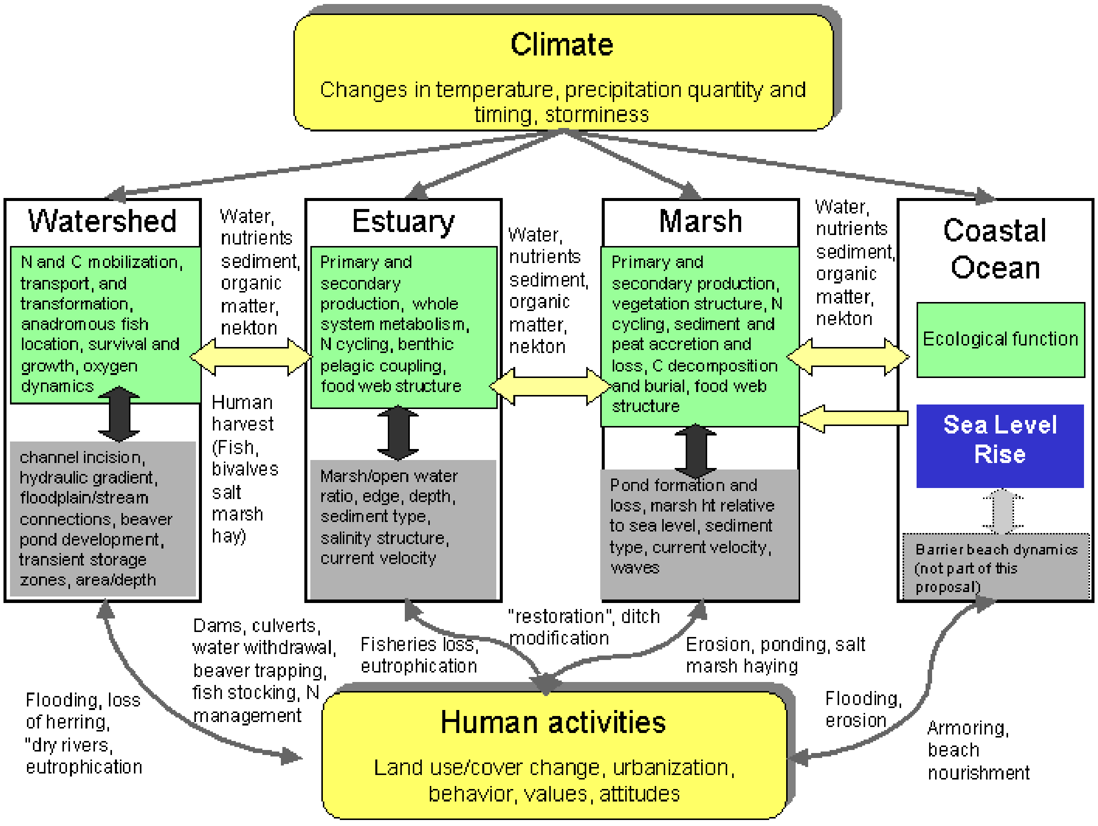


Figure 2.4. Conceptual model for the current proposal illustrating the greater emphasis on linkages between compartments, the human dimension, and geomorphology and geomorphic change. Program areas are now watershed, estuary, marsh, higher trophic levels, and modeling and synthesis.

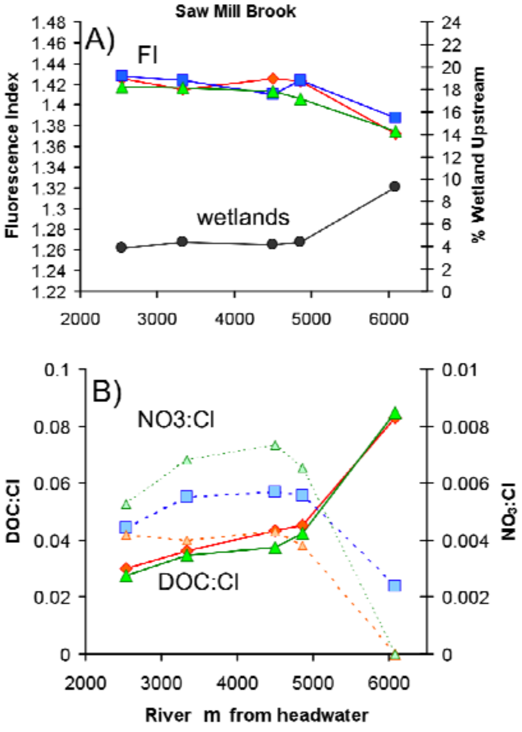


Figure 2.5. Biogeochemical response when an urban headwater stream flows into a floodplain dominated valley bottom. Data are from Saw Mill Br., a headwater of the Ipswich R. A) Change in upstream wetland % and DOC fluorescence index, a measure of DOC quality, along a 6000m transect. B) Change in NO_3:Cl and DOC:Cl along the same transect. The valley bottom starts at 5000m. High NO_3 in the headwater rapidly declines over a short reach, while DOC increases and quality changes, due to strong connectivity with floodplain soils (unpublished LTER data).

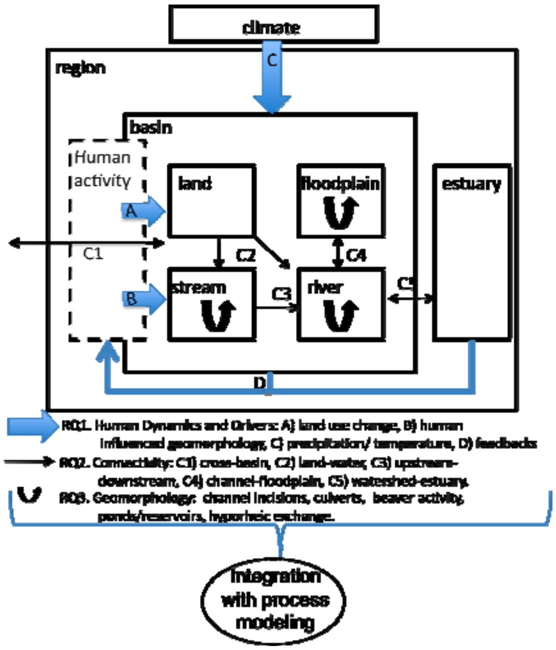


Figure 2.6. Conceptual overview of the watershed research questions. The set of questions will be linked via process-based models to understand how the system operates as a whole.

Figure 2.7. Example of an 8-category map at 45-cm resolution from within the Plum Island watershed. This information can establish the proportion of each land cover category at the household parcel-level, allowing differentiation among various forms of residential land, not possible with previously available maps.

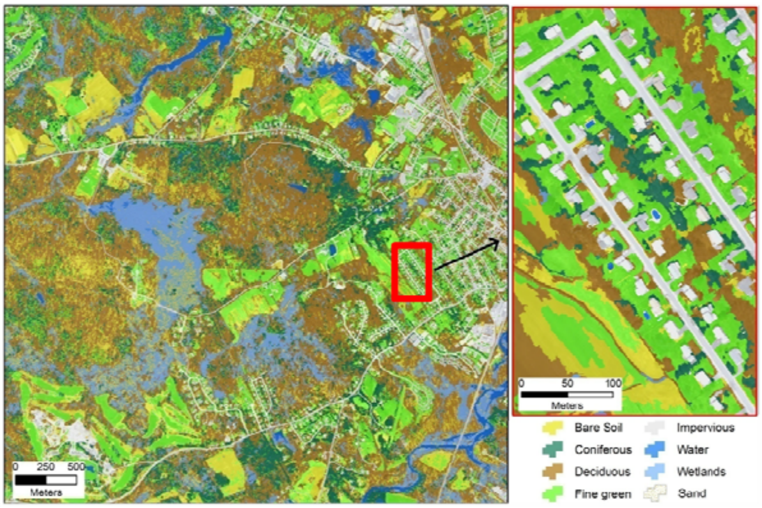
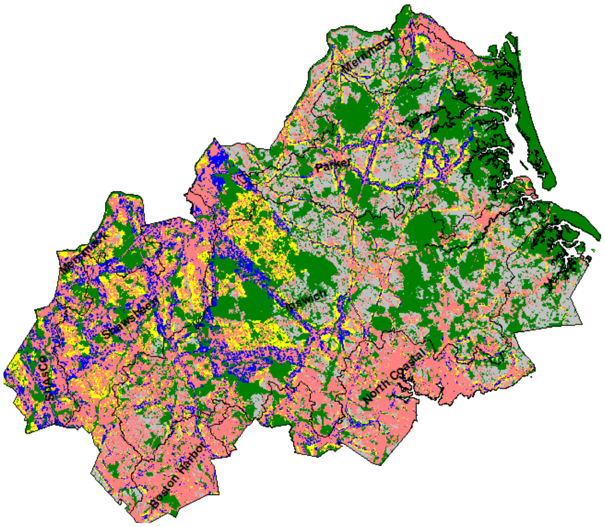


Figure 2.8. Map comparing business-as-usual vs. smart growth scenarios in the year 2050 for the 26 towns of the Plum Island watersheds. Colors represent categories of change: Pink: developed in 2005; Green: legally protected from development; Gray: undeveloped in 2050 under both scenarios; Blue: new development during 2005-2050 under both scenarios; Yellow: developed in business-as-usual but not in the smart growth scenario, i.e. potential influence of smart growth policies. Maps such as these will drive hydrological and biogeochemical models to evaluate future conditions.



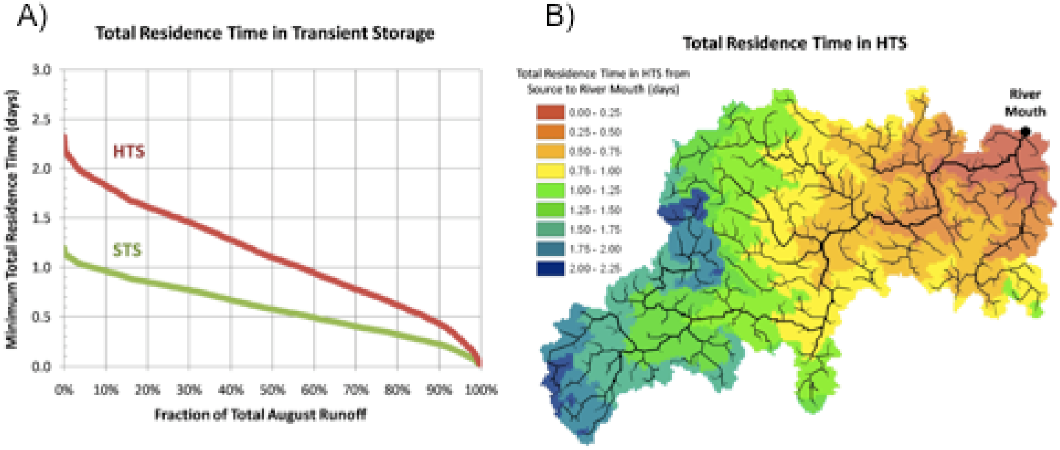
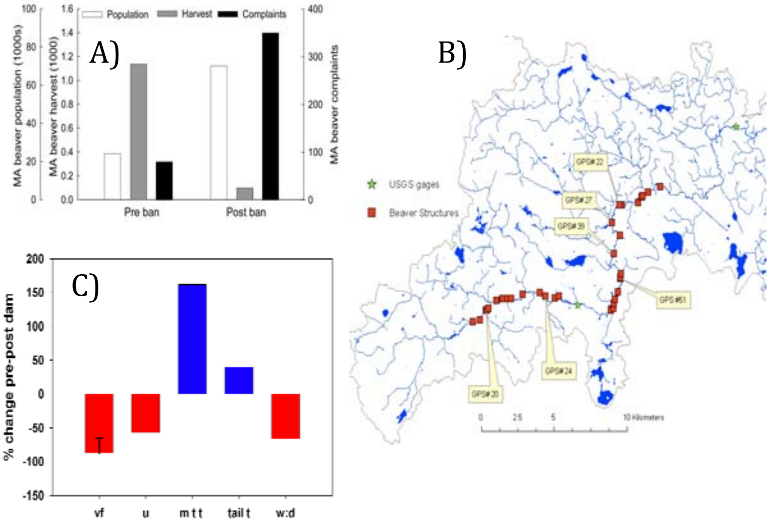


Figure 2.9. Results from river network model, incorporating transient storage dynamics. A) Whole-basin frequency distribution of residence times in surface and hyporheic transient storage (STS and HTS) under low flow, parameterized using results of solute addition experiments (Briggs et al. in press), and B) Map of the Ipswich river network showing predicted cumulative residence time in HTS for runoff originating from each grid cell (Stewart 2009). Under the current proposal, the model will be modified to account for other types of transient storage (e.g. floodplains) and geomorphic heterogeneity, including lakes and ponds.

Figure 2.10. Geomorphological impacts of beaver activity in the Plum Island basins. A) Change in beaver population since 1996 passage of state-wide ban on leg-hold traps (MDFW, 2009). B)Beaver structures in mainstem of the Ipswich R. in 2007, controlling 35-47% of head change over a 25km reach (unpublished LTER). C) Geomorphic impacts of beaver activity from preliminary pre and post beaver dam experiments in a 4th order stream reach (vf = NH_4 uptake velocity, mtt = mean travel time, u= water velocity, w:d=width/depth) (Briggs et al. AGU 2009).



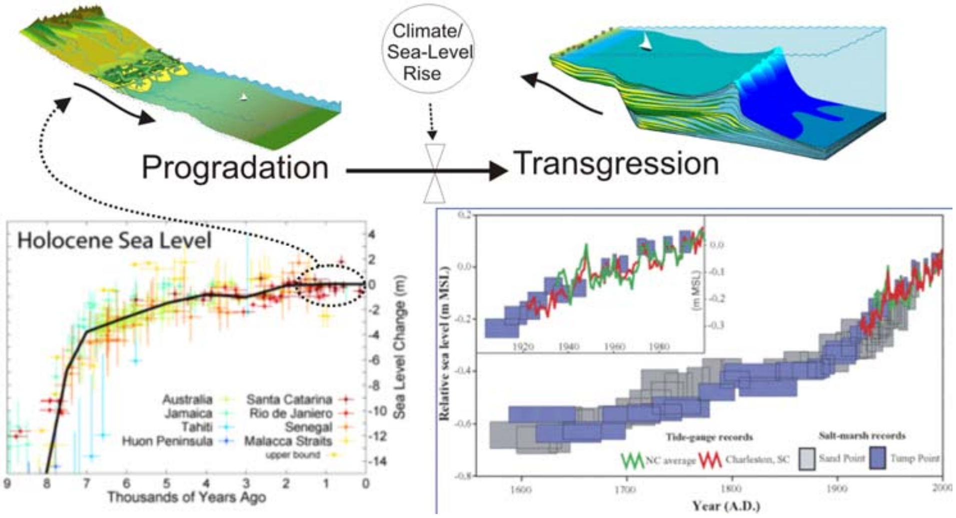


Figure 2.11. Sea-level was nearly static during the last several thousand years of the Holocene (lower left) and marshes prograded out onto the coastal shelf (upper left). According to theory, during progradation marshes equilibrate at the highest elevation within the tidal frame, accumulating sediment and serving as a sink for carbon and nitrogen. Total productivity will rise as the marsh landscape expands, but unit area productivity falls because marsh elevation exceeds the optimum for marsh vegetation. The last 3 centuries have witnessed accelerated sea-level rise (lower right from Kemp et al. 2009), and marsh transgression. Marshes are retreating inland and eroding. In transgression marshes become sources of carbon and nitrogen to the estuary. Total productivity declines as marshes contract. In the early stages of transgression, rising sea level will increase the discharge of nutrient-rich pore water from marshes to tidal creeks. Pore-water discharge decreases in the later stages of transgression as the marsh platform approaches mean sea level, reducing the hydraulic gradient and total length of creek bank.

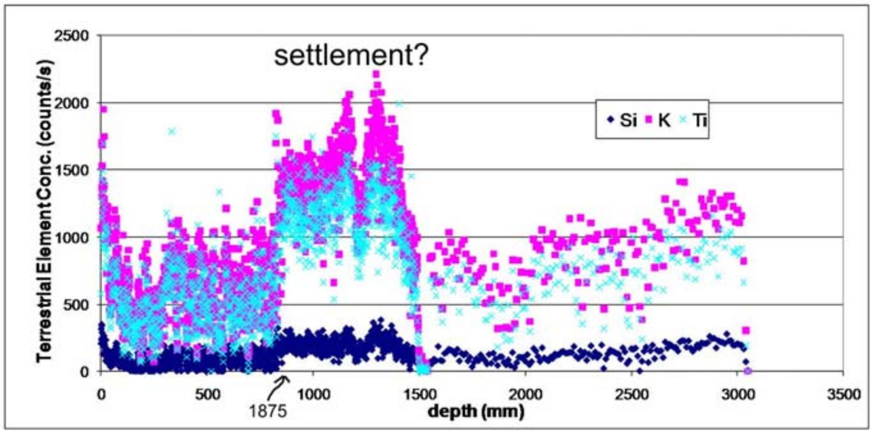


Figure 2.12. Concentration of terrestrial elements (Si, K, Ti) in PIE sediment core. High concentrations of Si, K, and Ti between 79 and 150 cm most likely are from European colonization and deforestation of the watershed. Loss on ignition data follow a similar pattern where there is a period of low organic matter during settlement, high organic matter after settlement, and decreasing organic matter in the top 10cm. Calibrated radiocarbon ages at 79 cm returned dates between 1802 - 1938 AD (mean=1875 AD).

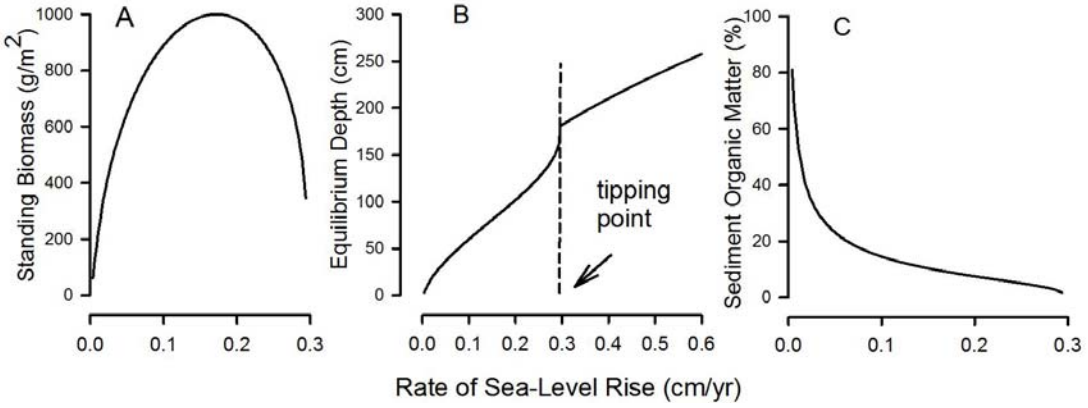


Figure 2.13. Model-computed (A) standing biomass, (B) equilibrium marsh surface depth below high water level, and (C) sediment organic matter concentration as functions of the rate of sea-level rise.

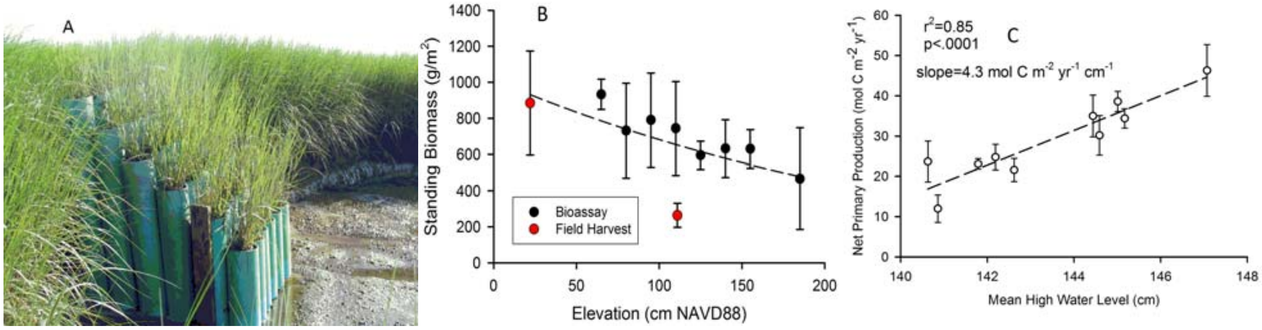


Figure 2.14. Different dimensions of the research on primary production at PIE, including (A) a bioassay designed to measure the response of marsh vegetation to relative elevation, (B) results from the bioassay showing biomass as a function of relative marsh surface elevation, and (C) annual aboveground NPP of *S. alterniflora* on permanent plots as a function of mean high water level recorded during the growing season. Experimental and field data confirm that production of *S. alterniflora* is closely related to relative marsh elevation.

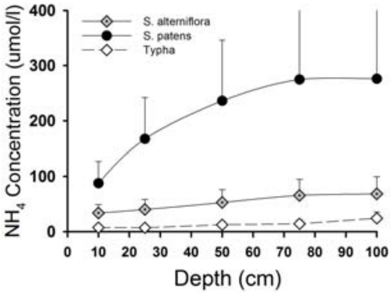


Figure 2.15. Geometric mean concentrations (+ 95% CI) of pore water ammonium by depth of sediment in high marsh dominated by *S. patens*, low marsh dominated by *S. alterniflora*, and a brackish *Typha* marsh.

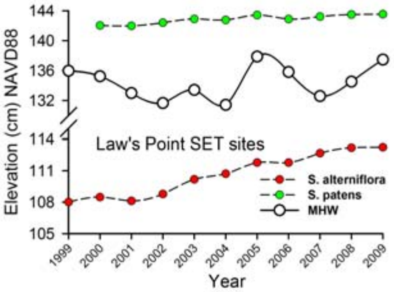


Figure 2.16. Relative, mean elevations of the marsh surface in the high marsh dominated by *S. patens* and low marsh dominated by *S. alterniflora*. Also shown is the annual mean high water level in Boston.

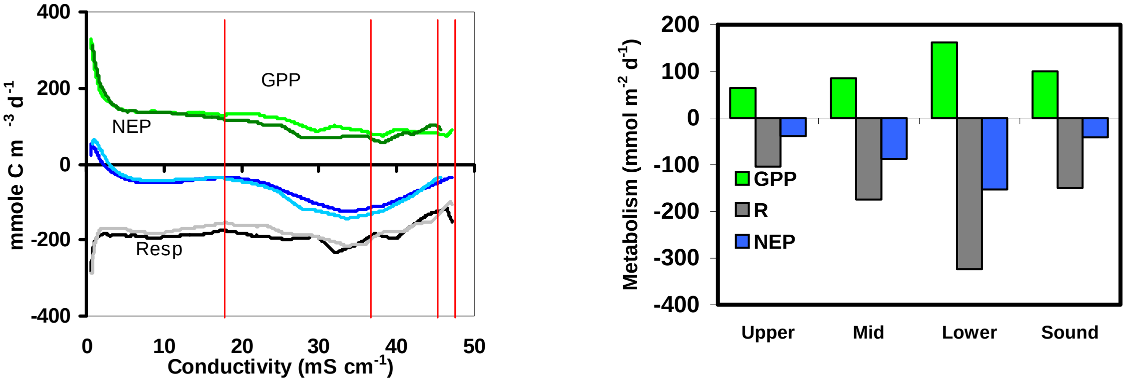


Figure 2.17. Spatial pattern of metabolism observed from diurnal measurements of free water oxygen concentrations measured along the entire length of the estuary. Note that each of the 4 regions of the estuary is net heterotrophic indicating a dependence on allochthonous sources of organic matter.

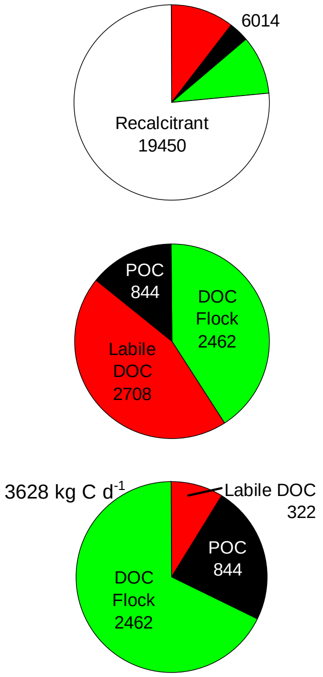
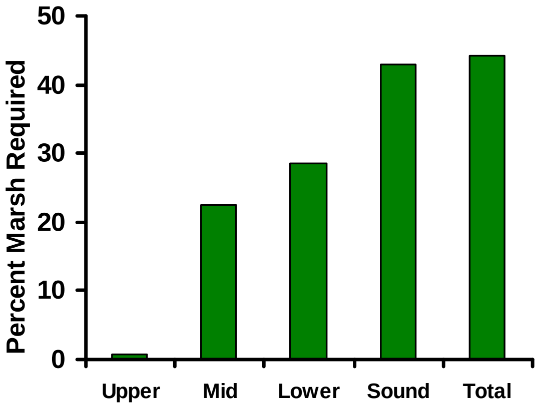


Figure 2.18. Bioassay experiments coupled with estuarine transit times indicate the fate of riverine sources of OM. We estimate that only 23% of all OM forms are utilized in the estuary, assuming that all forms of POC and the portion of DOC that floculates and settles within the estuary are consumed because of their nearly infinite residence time upon settling. Note that only 14% of labile DOC is utilized within the estuary; the remainder is exported to the sea.

Figure 2.19. Mass balance suggests that the negative NEP of the estuary must be sustained by organic matter produced by lateral intertidal marshes in the estuary. While riverine allochthonous OM inputs are sufficient to sustain heterotrophy in the upper 5 km of the estuary, the lower ¾ of the estuary requires the equivalent of 20 to 40% of marsh aboveground production. Our flux tower / aquatic creekshed sensor research activity is geared towards evaluating the pathways whereby this marsh coupling occurs.



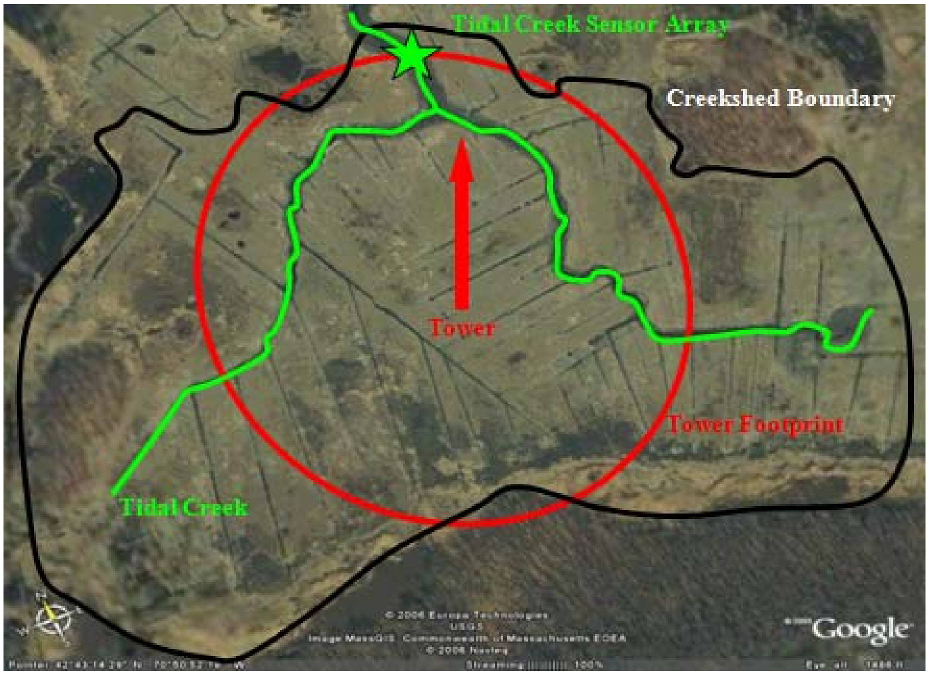


Figure 2.20. Basic configuration of flux tower and tidal creek sensor array within a 2nd order salt marsh drainage creekshed. This is just an example to show how the tower and sensor array might be situated. Ideally the tower will capture a fairly uniform patch of marsh which drains into a creek where the DIC flux can be monitored.

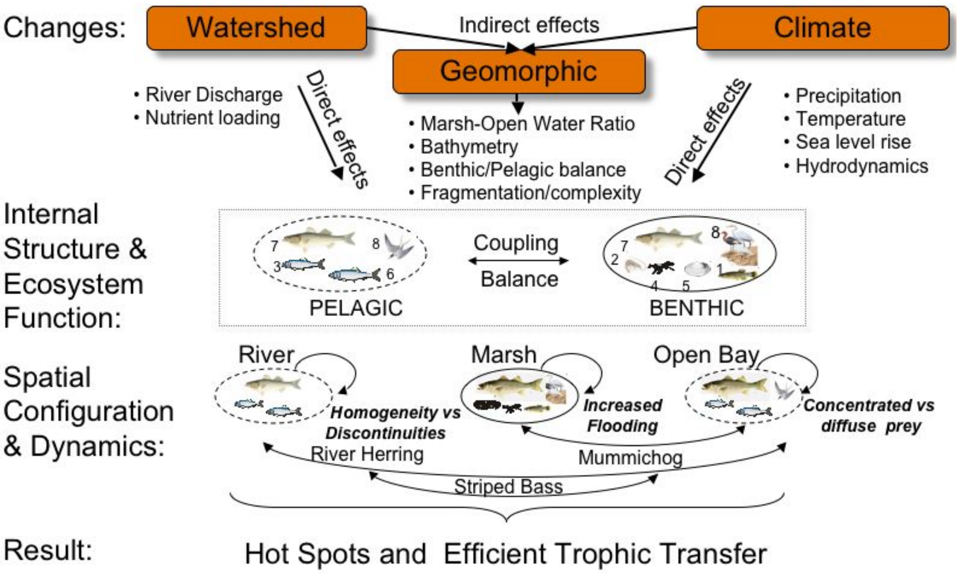


Figure 2.21. Conceptual approach to Higher Trophic Level research indicating the importance of internal connections within habitats or ecosystems, benthic pelagic food webs, spatial configuration, and dynamics and linkages among ecosystems by motile organisms. Model organisms: 1) mummichog (fish, *Fundulus*) and 2) grass shrimp (*Paleomonetes* sp.) as key small nekton in marsh and benthic food webs, 3) Atlantic silversides, a small fish of open bay, pelagic food webs, 4) sand shrimp (*Crangon* sp), open bay, benthic food webs, 5) softshell clam (*Mya*), a filter feeder associated with open water intertidal areas and an important fishery 6) river herring, anadromous species that integrates across fresh, estuarine and ocean,7) striped bass (*Morone* sp.), an iconic top predator and an important fishery species and 8) waders and shorebirds.

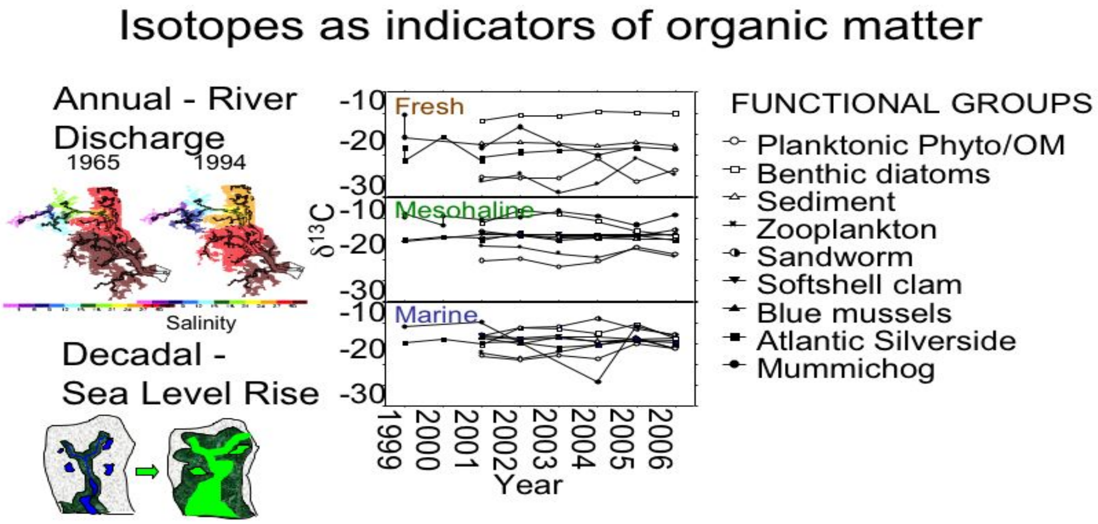


Figure 2.22. Isotopes of functional groups are used to indicate changes in organic matter sources and benthic/pelagic food webs.

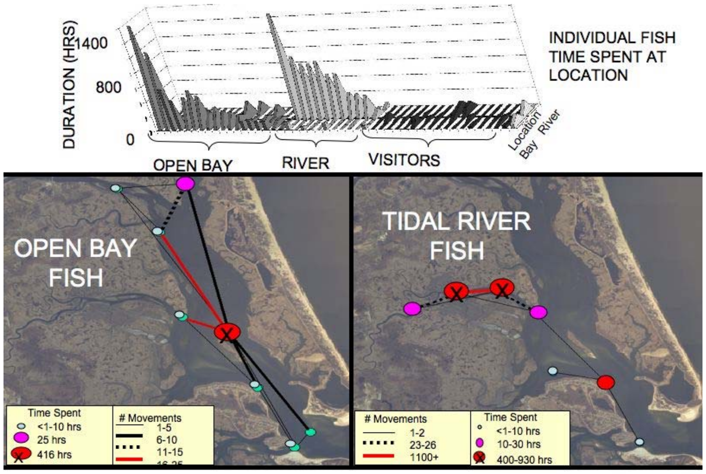


Figure 2.23. Although individual striped bass move throughout the estuary, they occupy distinct feeding locations in open bay and river areas, where they spend the vast majority of their time.

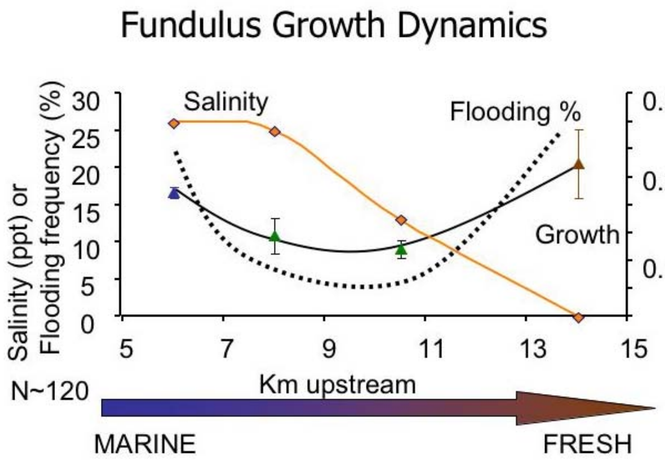


Figure 2.24. Mummichog fish growth controlled by position in the landscape and intra-habitat characteristics (Haas et al. 2009).

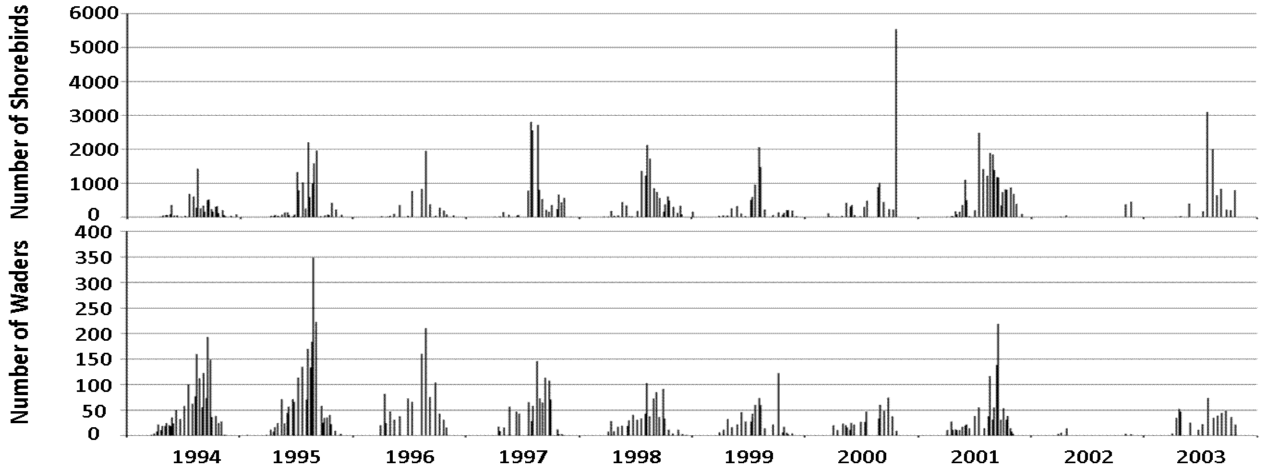


Figure 2.25. Trends in abundances of waders and shorebirds at Parker River National Wildlife Refuge, 1994-2003. Data collected by point counts from fixed locations on the refuge. Each line represents the sum total individuals at all points on that particular day. Counts were carried out by volunteer birders from mid March through early December, typically several times per month. In 2002, sampling was not carried out during the mid summer period. Abundances of both guilds peak in mid to late summer, which is their post breeding period. Waders numbers peaked annually at a higher level in the first few years of the survey compared to post 1998. Shorebird numbers appear stable in this 10 year period. Data from the Parker River National Wildlife Refuge.

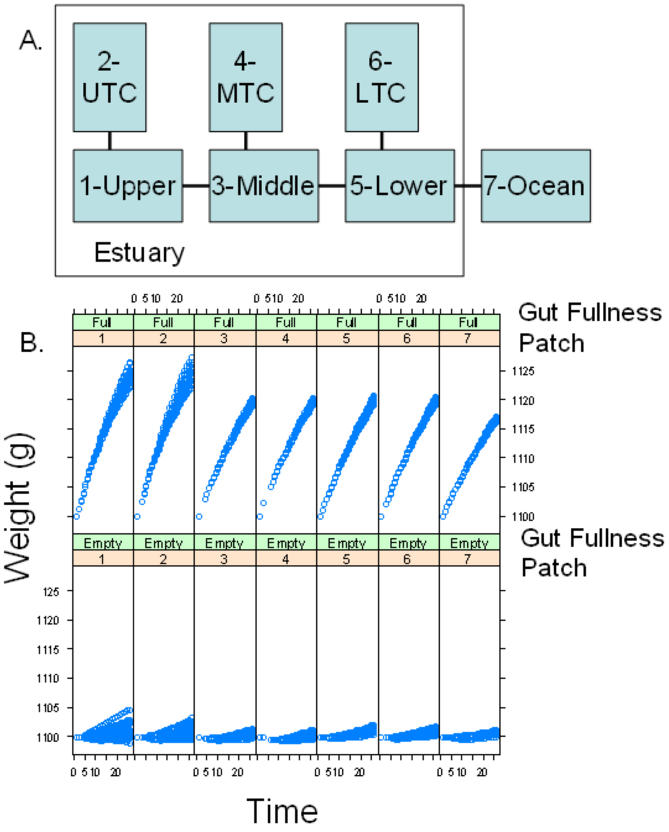


Figure 2.26. Behavioral model of striped bass movement. A) Patches in dynamic optimization model. B) Weight gain through time.

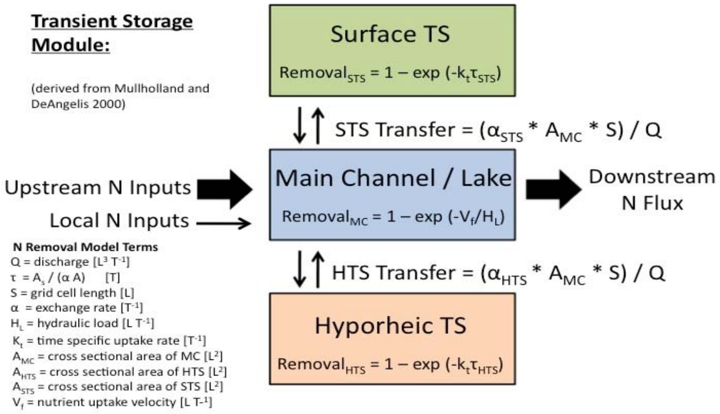


Figure 2.27. Schmatic of watershed modeling illustrating how transient water storage is simulated.

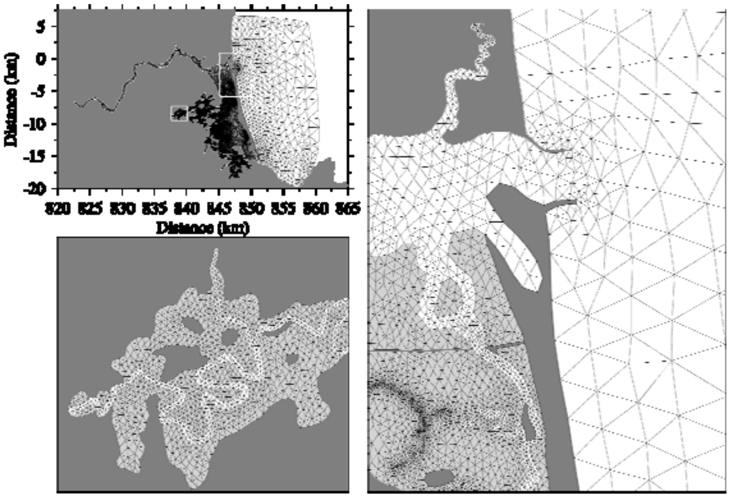


Figure 2.28. Full model domain of PIE-FVCOM (upper left), with grid details for the upper Parker River (lower left) and mouth of the Merrimac River and connection to PI Sound (right).

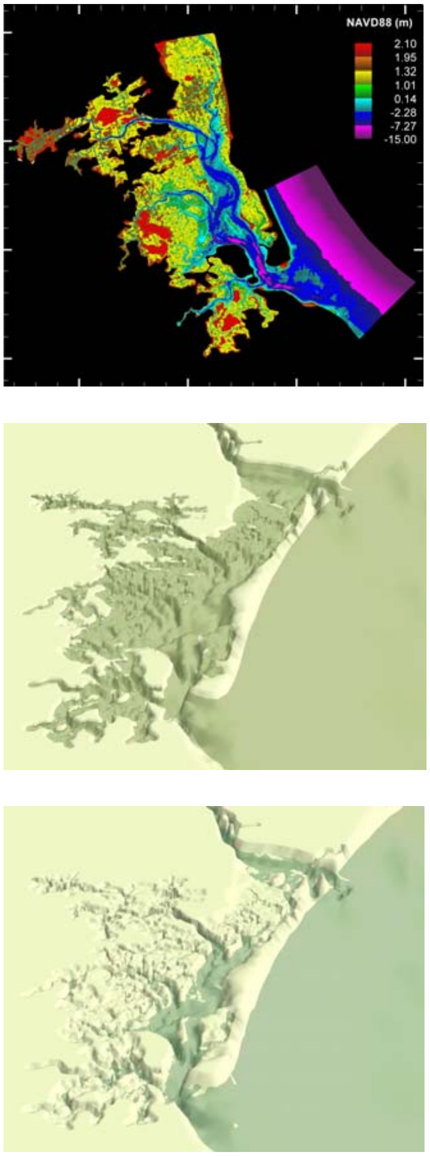


Figure 2.29. PIE marsh topography-bathymetry model (top) and extent of flooding and drying of PIE estuaries and Merrimack River during spring high (middle) and low (bottom) tides.

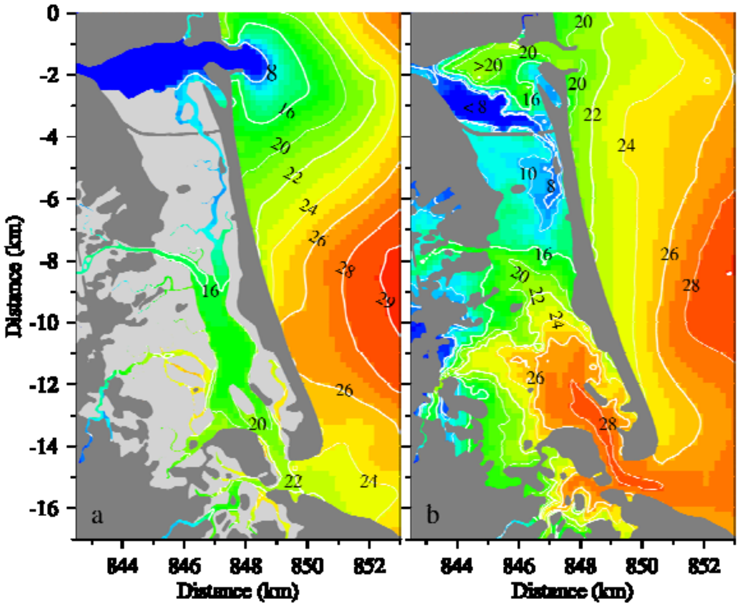


Figure 2.30. Simulated salinity distribution at low (a) and high (b) tides. Freshwater discharge from Merrimack R. is forced into PI Sound during flood tide (b).

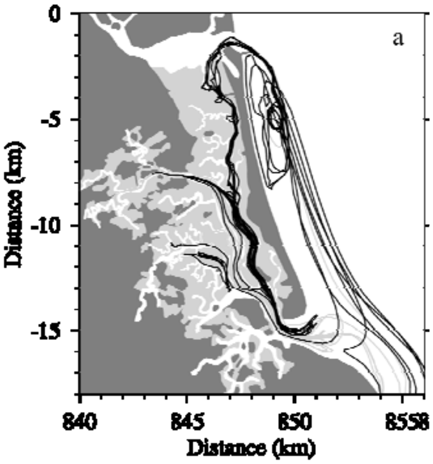


Figure 2.31. Simulated drifter release from PI Sound illustrating residual clockwise circulation. Drifters were released in PI Sound and Merrimac R.

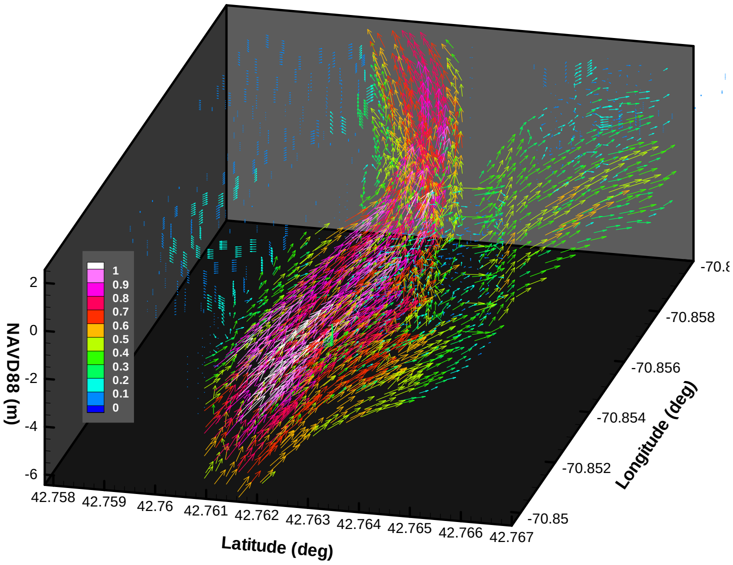


Figure 2.32. Close up of 3D velocity vector field (m/s) of Parker R. at Little R. split. Note low velocity eddy (middle, right of split), and shallow marsh creek flooding (blue on left). PIE-FVCOM uses 6 equally spaced sigma layers of differing depths based by bathymetry-topography and modeled water elevation.

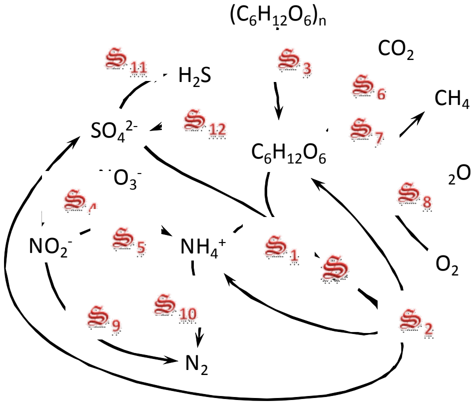


Figure 2.33. Example of a distributed metabolic network involving N, S and C cycling catalyzed by biological structures, $\mathfrak{S}$.

MEP:

$$\max\left\langle \frac{dS}{dt} \right\rangle_{t_j} = -\frac{A}{T\delta_t}\int_{x_L}^{x_R}\int_{t_j}^{t_j+\delta_t}\sum_i r_i(\mathbf{c},\mathfrak{S};\boldsymbol{\eta})\Delta G_{r_i}^{\dagger}(\mathbf{c};\boldsymbol{\eta})\,dtdx$$

$$wrt: \quad \boldsymbol{\eta}(t,x), \boldsymbol{\sigma}(t,x)$$

subject to :

$$\boldsymbol{\eta}_L \le \boldsymbol{\eta}(t,x) \le \boldsymbol{\eta}_U \qquad \frac{\partial \mathbf{c}(t,x)}{\partial t} = \frac{\partial^2 \mathbf{c}(t,x)}{\partial x^2} - Pe\frac{\partial \mathbf{c}(t,x)}{\partial x} + \frac{1}{\varphi}\boldsymbol{\Lambda}_1(\boldsymbol{\sigma})\mathbf{r}(\mathbf{c},\mathfrak{S};\boldsymbol{\eta})$$

$$0 \le \sigma_i(t,x) \le 1 \qquad \textit{and}$$

$$\sum \sigma_i(t_j,x_k) = 1 \;\forall\; j,k \qquad \frac{\partial \mathfrak{S}(t,x)}{\partial t} = D_{\mathfrak{S}}\frac{\partial^2 \mathfrak{S}(t,x)}{\partial x^2} + \frac{1}{\alpha_S}\boldsymbol{\Lambda}_2(\boldsymbol{\sigma})\mathbf{r}(\mathbf{c},\mathfrak{S};\boldsymbol{\eta})$$

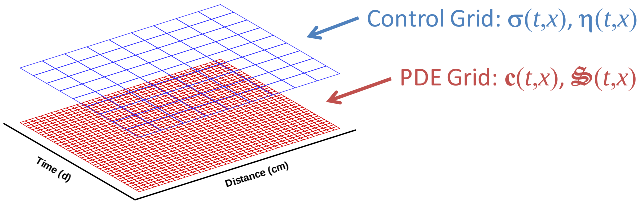


Figure 2.34. Mathematical 1D example of the MEP-based metabolic model. Entropy is maximized (top equation) over space and time by changing metabolic pathway expression, $\sigma_i(t,x)$, and thermodynamic efficiency, $\eta_i(t,x)$. Constituents, $\mathbf{c}(t,x)$, and biological structures, $\mathfrak{S}$, are subject to transport and reaction constraints. The resulting PDE optimal control problem is solved on two spatial grids.

Table 2.1 Long-term core measurements conducted at regular intervals in watersheds, estuary and coastal ocean. Data sets and methods are available on the PIE LTER web site (http://ecosystems.mbl.edu/pie/data). LTER core areas: 1) Primary production, 2) Organic matter, 3) Nutrients, 4) Disturbance, 5) Dynamics of populations.

PROGRAMMATIC AREA & LOCATIONS	**CORE AREA**	**VARIABLES**	**FREQUENCY**	**METHOD**
WATERSHED Q1 NADP sites (Lexington & Truro, MA)	1	Wet/Dry temperature (T), insolation, precip, wet & dry N/P deposition	Hourly	NADP program
WATERSHED Q1 PIE weather station, Marshview Field Station	1	Temp, precipitation, humidity, wind speed/direction, barometric pressure, solar radiation, PAR	15 minute and daily	Campbell Scientific weather station
WATERSHED Q1 NCDC sites (Boston, Groveland, Bedford, Haverhill, Lawrence, Marblehead, Middleton, Reading, Ipswich & Newburyport, MA)	1	Temperature, precipitation	Daily	NOAA, National Climatic Data Center
WATERSHED Q1 Sub-catchment headwater streams of Ipswich & Parker Rivers (suburban, forest, and wetland dominated catchments)	2, 3, 4	Temp, H_2O level, NH_4^+, NO_3^-, PO_4^{3-}, DO(N, P &C) PO(C&N), TSS	Monthly grab samples	Data logger and grab samples, Alpkem autoanalyzer, Lachat autoanalyzer, Shimadzu TOC/TN, CHN, gravimetric
WATERSHED Q1 Sub-catchment headwater streams of Ipswich & Parker Rivers	2, 3, 4	NO_3^-, Total nitrogen, carbon, and phosphorus	Monthly composite samples (4x per day)	SIGMA autosampler and logger, Alpkem autoanalyzer, Shimadzu TOC/TN
WATERSHED Q1 Export at Ipswich, & Parker dams	2, 3	Temp, NH_4^+, NO_3^-, PO_4^{3-}, DO(N, P &C) PO(C&N), TSS (grabs). NO_3^-, Total C, N, and P (autosamplers).	Weekly Monthly grabs, plus two-day composite sampling using autosampler	SIGMA autosampler and logger, Alpkem autoanalyzer, Shimadzu TOC/TN, CHN, gravimetric
WATERSHED Q1 Export at Ipswich & Parker River dams	4	Riverine discharge	Daily	USGS station

MARSH Q2 Parker & Rowley River marshes	1	Macrophyte productivity	Monthly-semi monthly, grow season	Phenometric
MARSH & ESTUARY Q2 & Q3 Parker & Rowley River marshes	1	Algal biomass	Monthly - grow season. 5 benthic habitats in marsh	Pigment analysis
MARSH Q2 Parker & Rowley River marshes	2, 3	Accretion	Monthly (grow season), semi-annual	SET tables marker horizons, sedimentation plates
MARSH Q2 Parker & Rowley River marshes	2, 3, 4	Porewater - NH_4^+, NO_3^-,PO_4^{3-}, DO(C&N) Eh, pH, S^2, conductivity	Monthly - bimonthly	Diffusion samplers
MARSH Q2 Parker & Rowley River marshes	4	Groundwater height	10 minute intervals	Pressure transducers
ESTUARY Q3 Parker River and Plum Island Sound	1, 2, 3, 4, 5	Light, DO, T, Cond, NH_4^+, NO_3, PO_4^3, DO(N,P,C), PO(C,N), TSS, Chl, DO, Prim. Prod. & Resp., phytoplankton & zooplankton preserved samples	Semi-annual, high/ low discharge conditions	Licor, YSI sondes, autoanalyzer, UV & high temp oxidation, CHN, gravimetric, acetone/fluorescence, O2, DIC, direct count, net tows
ESTUARY Q3 Parker River and Plum Island Sound. Three locations, oligohaline, brackish, marine (upper, mid, sound)	1, 2, 4	Temp, DO, conductivity and depth	0.25 hr	YSI water quality sondes
ESTUARY Q3 NOAA/NOS, Boston, MA	4	Sea level	Monthly	NOAA/NOS station
ESTUARY Q3 Parker River and Plum Island Sound	5	Phytoplankton	Semi-annual, high/ low discharge conditions	CHEMTAX, HPLC pigments
ESTUARY Q3 Parker River	2, 3, 4	Benthic fluxes	Semi-annual	Core incubations
ESTUARY & HIGHER TROPHIC LEVELS Q3 & Q4	2,3	Functional group representatives: Sediments, POM,	Yearly at locations along a transect from	C, N Stable isotopes – IRMS Sulfur and deuterium

Ipswich, Parker & Rowley Rivers and Plum Island Sound		microbes, macrophytes, benthic diatoms, zooplankton, *Geukensia*, *Mytilus*, *Mya, Crassostrea Nereis*, *Fundulus*, *Menidia,* Striped bass	fresh to marine	on select samples
HIGHER TROPHIC LEVELS Q4 Ipswich, Parker & Rowley River marshes and Plum Island Sound	5	Birds	Monthly (May – Oct) in conjunction with Audubon and USFWS - Parker River National Wildlife Refuge.	Direct counts Lag to clear final data to LTER posting through USFWS is 2 years.
HIGHER TROPHIC LEVELS Q4 Parker & Rowley Rivers and Plum Island Sound	2, 3, 5	Nekton (fish, crabs and shrimp)	Monthly May - October	Seine. We will use this approach only to inter-calibrate the new flume net approach and then discontinue it as the variability in the data were unacceptably high.
HIGHER TROPHIC LEVELS Q4 Parker & Rowley Rivers and Plum Island Sound	2, 3, 5	Nekton (fish, crabs and shrimp)	Monthly May - October	Flume nets provide a more stable estimate of small nekton use of marsh habitats and will replace the seine surveys after intercalibration.
HIGHER TROPHIC LEVELS Q4 Parker & Rowley Rivers and Plum Island Sound	5	*Fundulus & Menidia* dynamics	Monthly May – October, spring high tides	New work using the flume net data combined with length/frequency and otolith analysis of growth.
HIGHER TROPHIC LEVELS Q4 Watershed portion of Ipswich, Parker & Rowley Rivers	5	Anadromous fish	Yearly	New work in watershed using tags and direct counts in cooperation with local watershed association groups.

SECTION 3: SITE MANAGEMENT

GOVERNANCE AND COORDINATION

Overall direction and management are provided by lead PI, Anne Giblin, and an Executive Committee. The Executive Committee consists of Giblin, the leaders of each programmatic area, and a representative of the social sciences (currently Gil Pontius). The current program coordinators are:

Program area	Coordinator
1) Watersheds	Wil Wollheim
2) Marshes	Jim Morris
3) Estuary	Chuck Hopkinson
4) Higher Trophic Levels	Linda Deegan
5) Synthesis and Modeling	Joseph Vallino

The Executive Committee is consulted on all financial matters, approves budgets and supplement requests, collects information for annual and final reports from other members of their program area, and facilitates transitions in leadership. Coordinators keep all members of the LTER informed about activities and findings in their program area, including those of other grants closely related to the LTER. Each program area holds regular meetings 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.

During the last grant we had several changes in leadership. Anne Giblin took over for Chuck Hopkinson as lead PI. Hopkinson is still very actively involved and has taken over the direction of our Estuary program from Bruce Peterson. Wil Wollheim replaced Charles Vorosmarty as watershed coordinator when Vorosmarty moved to City College of New York. As was discussed in the previous section, our former program area of benthos has been eliminated in this renewal and the research and long-term monitoring were merged into Estuary and Higher Trophic Levels.

Elizabeth Duff, of Massachusetts Audubon serves as our education coordinator, and is included in all discussions that involve education and outreach. Robert Buchsbaum, also from Massachusetts Audubon, coordinates with government agencies and NGOs in the PIE-LTER area as part of his position. Buchsbaum also actively participates in many aspects of higher trophic level and marsh research at PIE so he and Duff have a thorough understanding of PIE science and education. This allows them to very effectively assure that PIE outreach activities are targeted to the proper audiences.

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. As an example, all of the PIs and senior personnel, as well as key research assistants, participated in monthly video-conference calls in the year leading up to this renewal to develop our new questions and research approaches. This approach proved very successful, and we will continue to hold several meetings each year this way to supplement our annual meeting.

Each spring we hold a meeting of all scientists, post-docs, students and research assistants associated with the project. All personnel working on the PIE-LTER and 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 to attend and give presentations.

ENCOURAGING NON-LTER SCIENTIST PARTICIPATION AND COORDINATION

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. The major way we have been able to broaden long-term participation in the project is by writing grants with non-LTER investigators. We coordinate logistics such as housing and boats through our web site. 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. 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.

INCREASING DIVERSITY

At the K-12 level we have increased the number of minority students participating in the program by adding the Collins Middle School in Salem 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 targeted increased coordination with Brown and the MBL-SES program, which have active minority recruiting programs, to help us increase minority participation. At the graduate, and post-graduate level we advertise positions widely. The PIs at each of our institutions use the list serves set up by scientific societies and their own human resources departments to assure a wide distribution of position announcements.

PI ADDITIONS

We are adding Colin Polsky (Clark University) and Christopher Neill (MBL) to the project with this renewal. Polsky has been involved in the PIE LTER for the last 5 years through his collaboration with PI Gil Pontius on Clark University's "HERO" program and through the social science supplements to the PIE LTER. Polsky broadens the expertise in social science within the LTER and will further increase undergraduate and graduate involvement. Neill brings expertise on the impact of changes in land use and land cover on forest and terrestrial plant communities and on water and material exports from the terrestrial side. He will form a link between the social science research being done at Clark and work on watershed exports and processing being done by UNH. Neill is currently director of the Brown MBL program so he will be able to help increase undergraduate and graduate participation.

FIELD FACILITIES

Our field facilities were greatly expanded in 2003 when MBL purchased the Marshview Farm in Newbury, MA. This facility has sleeping space for 13, a small laboratory, and 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 LTER needs over the last 7 years. Most of the time we have been able to also accommodate students, PIs, and post-docs from related projects, but requests at some times of the year now exceed our capacity. We have provided housing for additional researchers (such as scientists doing short term comparative field studies from other LTERs) whenever we could but in summer space is often limited. While our space is sufficient for direct LTER needs, the overall growth of research at the site may soon be constrained by our facilities. We are looking for ways to alleviate this. During the last funding cycle we received NSF funds for a planning grant to remodel the Marshview Farmhouse and barn. We used this plan, and our experience on the needs of the current researchers, to submit a grant to upgrade the facility. If this grant is not successful we will continue to search for other funding avenues and have the support of the MBL development office to pursue private funds for this purpose. We are also instituting a small daily fee for outside projects for overnight housing to help maintain and support the facilities and docks.

SECTION 4: DATA INFORMATION AND MANAGEMENT

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 Sound Estuarine Ecosystem and its watersheds. This centralized network provides researchers associated with PIE LTER access to common information and data in addition to centralized 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 LTER are committed to the integrity of the information and databases resulting from the research.

PIE LTER information and databases are stored on a MBL Microsoft Windows server with a level 3 RAID array that is backed up on tape nightly. Once a month a tape is removed and stored in a separate building.

Access by the public and scientific community at large to PIE LTER data and information is provided through the PIE LTER Web site, http://ecosystems.mbl.edu/PIE. Near real time weather data (helpful when planning research schedules) are also available on our field station website, http://www.pielter.org/. The PIE LTER home page has been active since late 1998 and contains information on personnel, data, published and unpublished papers, reports and School Yard education. The data section is broken down into four sections consisting of Program Areas, Education and Outreach, Physical Characteristics and Database Links. PIE maintains an internal database archive of datasets from which the home page is updated annually. Datasets on our web site are updated more frequently as investigators add data. The organization of the PIE home page basically mirrors the internal database archive in nomenclature, which allows for easy updating of datasets. Archived data on MBL's server can be directly accessed by MBL researchers and non-MBL researchers have access to a secure FTP web site at MBL for archival of data (both unprocessed and processed).

Data Management and Coordination of Research Programmatic Areas

The information management team consists of: Anne Giblin (Lead PI), Joe Vallino (PI), Robert (Hap) Garritt (IM), Gil Pontius (PI) and additional research assistants associated with program areas. The team has the necessary leadership, knowledge and technical expertise for creating and maintaining the PIE LTER 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 29 years experience in ecological research, an MS in Ecosystems Ecology and is very active in PIE LTER 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.

Individual researchers are responsible for providing data in each of the core programmatic areas in the PIE LTER. Our six existing areas (Watersheds, Marshes, Planktonic Food Web, Benthos, Higher Trophic Levels and Synthesis) will be merged into five following our new organizational structure (Watersheds, Marshes, Estuary, Higher Trophic Levels, and Synthesis) and data from benthos will be moved to the Estuary section. 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

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. Research conducted using the facilities of the PIE LTER is expected to comply with the following policy: All researchers will provide digital copies of data to the data manager. Data files will include accompanying documentation files that will 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) 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 or during field sampling trips, in addition to announcements during our Annual Spring PIE LTER All Scientists Meeting.

Data Accessibility and Timelines

Researchers on the PIE LTER are required to contribute data to the PIE LTER database. Researchers on associated projects have been and will continue to be encouraged to both publish and 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 is typically posted on the PIE web site within one to two years and selected data is 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))."

PIE data sets and information are easily accessible to PIE LTER scientists, local, regional, and state partners and the broader scientific community. 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 databases. PIE data on the web site is accompanied by a metadata document, which requests (based on an honor system) those users of the data to notify the corresponding Principal Investigator about reasons for acquiring the data and resulting publication intentions. During 2010, as the Data Access Server interface developed by the LTER Network Office (LNO) becomes fully functional, we will implement the interface as a means of registering and documenting 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 is represented in Table 4.1. Analysis of year 2009 PIE web server logs of non-associated PIE LTER investigators and others indicate there were 1709 hits on specific data sets by 643 unique visitors (averaging 4 hits per day). Researchers at PIE also get 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, Metacat Data Catalog and EcoTrends and has been involved with LTER Network EML workshops. Hap Garritt is a member of the LTER IM Executive Committee (2007-2010) and also the Unit Dictionary and GIS Information Manager working groups. Chuck Hopkinson continues to serve on the LTER Network Information System Advisory Committee (2005-present). PIE has been contributing samples and data to the Microbial Inventory Research Across Diverse Aquatic LTERs project (MIRADA) and we will be participating in a MIRADA LTER post ASM workshop at MBL in Woods Hole, MA, Spring 2010, which will address metadata structure for genomic and associated environmental data.

Current IM Projects

Data management is perpetual as we continue to update our existing online EML level 2.5 metadata to EML level 4-5 using the MS Excel based template. We are in the midst of adding extensive datasets from the Tidal Creek fertilization experiment project (TIDE) and from stations pertinent to PIE LTER watersheds available from the NOAA National Climate Data Center Weather Cooperative and the National Atmospheric Deposition Program. Development of a GIS information system for sharing PIE LTER GIS data has been an on going project for many years as we are attempting to bridge three GIS softwares (ArcGIS, IDRISI, RiverGIS). We are pursuing potential solutions via the Open Geospatial Consortium. The LTER IM GIS working group has also recommended development of a centralized portal for users to search, display, and access all site spatial data.

Future Objectives

Over the last couple of years PIE has been working on redesign of the web site attempting to provide information content and data that is comprehensible, easily accessible and manageable. Many design iterations have resulted but have proved unsatisfactory with regard to management of the site. Specific issues have occurred when responding to requests for search capabilities regarding relational content of various databases such as personnel, publications, Site DB and LTER core data sets to name a few. Our web designs were not capable of easily relating various types of content and were too static in nature. PIE participated in the 2009 LTER ASM workgroup “No dead end information website”, http://asm.lternet.edu/2009/workgroups/no-dead-ends-lter-information-website, led by Inigo San Gil (NBII/LNO) and Marshall White (LNO). The workgroup focused on a web content management system using Drupal, which is an open source content management platform. Robust content (publications, personnel directory, research/project information, data catalogs, maps, GIS layers, census databases and microbial work) management solutions essential to LTER were demonstrated. See Figure 4.1 for a graphical summary of what categories constitute the “information content” in the LTER context. After the workgroup we realized that a web based relational content management system should be pursued as a solution for our web redesign. PIE therefore plans to begin development of a Drupal based content web site during 2010. Several other LTERs either have or will be pursuing a Drupal content system that in combination with expertise at the LNO will help to standardize content management and also leverage resources in development of a robust web based content management system.

Table 4.1. Monthly use of PIE LTER data sets during 2009 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 and others not associated directly with PIE LTER.

	Year 2009	
Month	Hits by non-associated PIE LTER investigators and others	Number of Unique Visitors
JAN	84	50
FEB	182	62
MAR	111	59
APR	37	18
MAY	105	62
JUN	107	59
JUL	136	48
AUG	276	40
SEP	219	70
OCT	72	50
NOV	286	54
DEC	94	71
Annual Total	1709	643

[a] Non-browsing activity web hits have been excluded using filters for spiders, crawlers and domains not representing normal browsing activity.

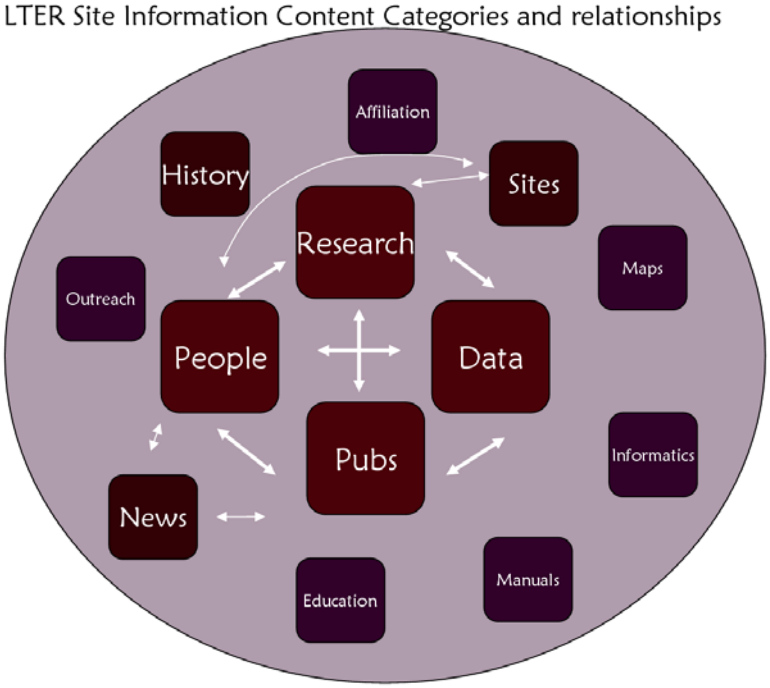


Figure 4.1 - The information content of LTER sites divided by category. The font size represents the consistence of the categorization across sites. Some of the relations between categories are depicted here (San Gil 2009, LTER post-ASM proposal “Facilitating cross-synthesis research: PASTA à la carte”.)

SECTION 5: OUTREACH AND EDUCATION PROGRAMS

The PIE LTER has a broad range of educational and outreach activities (Table 5.1). During the last two grant cycles we have been able to greatly expand our activities by partnering with non-profit conservation groups and local educators, and by continuing to build strong interactions with local, state and federal agencies. We are fortunate that a number of excellent educational programs existed in the Plum Island area. By leveraging PIE support we were able to help these programs expand both in the number of students served, and in educational content.

EDUCATION

Our goals are to: 1) excite students and teachers about coastal science, 2) encourage students to consider entering the field of science, 3) improve the environmental knowledge of the general public, and 4) inform stake holders about our LTER research.

LTER Schoolyard: This program has been highly successful as a result of collaboration with Mass Audubon and the Governor's Academy, and additional NSF funds (Expanded Schoolyard Supplements.) Teachers at the Governor's Academy, especially Susan Oleszko-Szuts, implement science modules for high school students using student monitoring of ribbed mussels and intertidal marsh plant distribution. In addition, 2-3 students per year are given paid internships to participate in PIE research over the summer and do small projects. Mass Audubon has implemented, with partial support from the LTER, a 5th –12th grade science education program "The Salt Marsh Science Project" (SMS) (http://www.massaudubon.org/saltmarsh). Under the guidance of Mass Audubon, students monitor vegetation transects, which allows them to assess the spread of invasive species including the common reed (*Phragmites australis*) and perennial pepperweed (*Lepidium latifolium*). Students also measure porewater salinities to relate them to vegetation patterns and study fish communities. SMS serves an average of 1000+ students per year and 50 teachers from 10 schools per year.

Mass Audubon's Education Coordinator and LTER education representative, Elizabeth Duff, trains local teachers in the field protocols, classroom lessons, data entry and analysis procedures. On field trips, students collect real data of interest to scientists. LTER and UNH scientists assist with data analysis, interpretation and feedback. Students share their findings at an annual conference and share data via the SMS web site. Duff has been honored for this work by the Gulf of Maine Council, winning the 2009 Visionary Award, which recognizes "innovation, creativity, and commitment to marine protection by businesses, environmental organizations, or individuals who are making a difference to the health of the Gulf of Maine."

In addition to maintaining this highly successful schoolyard program, Duff, helped forge a link between teachers, PIE-LTER research and local school curricula. Since 2004, 34 teachers have attended the PIE-LTER All Scientists Meeting, learning about PIE-LTER research, brain-storming ways it connects to the Massachusetts Science Frameworks, and discussing ways LTER scientists may support their teaching goals. To help teachers better understand the scientific presentations, we developed a glossary of scientific terms, and developed a presentation with suggestions for scientists presenting to non-scientists. We developed and delivered 3 courses on climate change and coastal communities, including 4 scientists presenting LTER research serving a total of 60 teachers. LTER scientists and graduate students shared their research on striped bass in an "Ocean Science Education Institute" for 50 youth and adults. These scientists also assisted a team of educators in developing and piloting a curriculum based on LTER bass research (available at http://www.massaudubon.org/saltmarsh/striper/). To help the greater community learn more about LTER science we have written and published five articles about LTER research in Mass Audubon's "Connections" magazine.

New Directions: In addition to continuing the work above, we would like to initiate additional stewardship activities in the region. We will encourage local students and citizens to reduce their carbon footprint, as well as participate in direct actions to improve the health of local ecosystems

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 have had both undergraduate and graduate students participate through the Clark Human-Environment Regional Observatory (HERO) program (http://hero.clarku.edu). Students analyze the causes and consequences of global environmental changes at local scales in faculty-led research projects. Our graduate student population grew to 32 during the last 6 years and should expand further. Christopher Neill, who is a new PI, and Director of the Brown-MBL Partnership and the Brown-MBL Joint Graduate Program, and will work to develop opportunities for Brown PhD and Masters students within the PIE-LTER. A pending Integrative Graduate Education and Research Traineeship (IGERT) grant, on which Giblin is a co-PI, would provide fellowships for 10 incoming Brown graduate students to link microbial processes and ecosystem biogeochemistry at PIE. 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 since 2004.

OUTREACH ACTIVITIES

Our goal is to increase the environmental knowledge of the general public, especially on issues related to watershed, estuarine and marsh processes. We do this by giving presentations to local NGOs and business groups (Trustees of Reservations, Essex County Greenbelt, Rotary, MBL Associates, Gulf of Maine Institute, Island Futures Group), writing articles for publications aimed at general audiences (*Sanctuary*, *Earthkeeper*, MBL *Catalyst*), publishing brochures, hosting science writers through the MBL science journalist program, and offering community-wide open houses. Mather and her students also developed “Adopt-a-Bass” and “Adopt-a-Herring” programs and web pages (http://www.Ipswich-riverherring.com), which help directly engage the public in our research. Unexpectedly, we had a number of conservation and sports groups adopt fish and promote the content of the web site, which greatly augmented the outreach value of the program (Frank et al. 2009).

We bring our technical expertise to a growing number of NGOs and regulatory and management agencies. Deegan heads the steering committee for CAMEO, (Comparative Analysis of Marine Ecosystem Organization), a partnership between the NOAA National Marine Fisheries Service and the NSF Division of Ocean Sciences forged to strengthen the scientific basis for an ecosystem approach to the stewardship of ocean and living marine resources. Deegan was also a delegate to the Copenhagen Climate Conference. Wollheim is a member of the Ipswich River Watershed Association (IRWA) Technical Advisory committee. Giblin is on the board of directors of the Gulf of Maine Institute. Pontius is an advisor to the Massachusetts Water Resources Research Center. Buchsbaum and Duff are members of the Great Marsh Habitat Restoration team which includes staff from a variety of state and federal organizations including EPA, USFWS, and NOAA. Buchsbaum is also a member of several committees working on habitat issues sponsored by the Gulf of Maine Council and is on the Management Council of the Massachusetts Bays Program (part of EPA’s National Estuaries Program).

Table 5.1. Participants in PIE's educational programs.

Category	# of individuals	Institutions
Schoolyard LTER program	**~1000 students/year** **~50 teachers/year**	*11 Middle and High schools in Boston & Plum Island area
High school interns	**11**	Governor's Academy (Byfield, MA)
Undergraduate interns and REUs	**56**	Clark University (16), Connecticut College (9), Middlebury College (3), Amherst College (1), College of Charleston (1), College of William and Mary (3), Colorado College (1), Colorado School of Mines (1), Gordon College (3), Grambling College (1), Louisiana State University (1), Pennsylvania State University (1), Rollins College (1), Sewanee University (1), Smith College (1), Syracuse University (1), Tufts University (1), Tulane University (1), UMASS Lowell (4), UMASS Amherst (1), U. New Hampshire (1) University of Vermont (1), Wellesley College (1), Wheaton College (1)
Undergraduate class projects	**78**	Boston University (10), +Clark (50), Wellesley College (7), Brown University (3), Vassar College (1), University of California, Berkeley (1), Kenyon College (1), Haverford College (1), SUNY ESF (1), Ripon College (1), Skidmore College (1), Dillard College (1)
Research assistants (Bachelor's)	**11**	Ecosystems Center, MBL
Graduate students	**32**	Clark University (7), Louisiana State University (3), UMASS Amherst (5), UMASS Boston (1), University of New Hampshire (5), University of South Carolina (5), Boston University (1), Colorado School of Mines (1), Connecticut College (1), MIT (1), Roskilde University (1), Virginia Institute of Marine Science (1)
Post-doctoral associates	**10**	Ecosystems Center, MBL (6), University of New Hampshire (1), University of Georgia (1), UMASS Dartmouth (1), University of South Carolina (1)
Affiliated graduate students	**14**	MIT (6), Boston University (5), U. of Vermont (1), Clark University (1), U. of Huston (1)
Affiliated post-docs	**8**	MIT (7), Boston University (1)
Field trips	**26**	MIT (6), MBL-SES (20)

*Schools - Collins Middle School in Salem, Essex Agricultural and Technical High School , Essex Elementary & Middle School, Ipswich High School, Holton Richmond Middle School in Danvers, Newbury Elementary School, O'Maley School in Gloucester, Rockport Middle School Rupert Nock Middle School in Newburyport, River Valley Charter School In Newburyport, Stoneridge Montesorri School in Beverly. Collins Middle School is in an urban area and has a significant minority population.

+ Undergraduate Clark University students examined salt marsh microbial diversity in control and fertilized plots but did not visit the field site.

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Supplemental Table 1.2 Data sets available on PIE LTER WWW site, http://ecosystems.mbl.edu/pie/data. On-Line Status, (O) for available, (P) for pending. Use of the data by non-LTER investigators is detailed in Section 4 on information management.

Dataset	**Dataset Title**	**Lead PI**	**Begin Year**	**End Year**	**On Line Status**
WATERSHEDS					
WAT-VA-Inputs	Water chemistry of the Ipswich & Parker Rivers	Wollheim	1993	2008	O
WAT-VA-Load	Annual nutrient loading and yield to Plum Island Estuary	Wollheim	1993	2008	O
WAT-VA-SigmaNutrients	Daily nutrients from Sigma auto samplers in various watershed locations	Wollheim	2001	2009	O
WAT-YSI-SIGMA-timeseries	Nutrient grab samples from 6 sites of the Ipswich and Parker Rivers	Wollheim	2001	2009	O
WAT-PR-ParkerDischarge01101000	Parker River daily discharge @ Byfield, MA	Wollheim	1945	2009	O
WAT-IP-IpswichDischarge01102000	Ipswich River daily discharge near Ipswich, MA	Wollheim	1930	2009	O
WAT-IP-IpswichDischarge01101500	Ipswich River daily discharge near S. Middleton, MA	Wollheim	1938	2009	O
WAT-VA-StreamNutrient	Rain event nutrient time course for 8 streams	Hopkinson	1992	1993	O
WAT-IP-Catchments	Nutrients of Ipswich River, 1st to 4th order catchments	Hopkinson	1999	2000	O
WAT-MBL-IP-catchments	Nutrients of Ipswich River, 1st to 4th order catchments, to standardize IDs	Hopkinson	2000	2002	O
WAT-UNH-IP-catchments	Nutrient data set of Ipswich River headwaters with help from Ipswich River Watershed Association.	Vorosmarty	2001	2002	O
WAT-UNH-PR-catchments	Nutrient data set of Parker River headwaters with help from Parker River Cleanwater Watershed Association.	Vorosmarty	2001	2002	O
WAT-IP-1998Monthly	Nutrients of Ipswich River main stem, major tributaries	Hopkinson	1998	1999	O
WAT-IP-MonthlySampling	Nutrients of Ipswich River main stem, major tributaries	Hopkinson	1999	2001	O
WAT-VA-rainfall	Wet deposition solutes for Ipswich River basin	Hopkinson	2000	2001	O
WAT-YSI-FishBR-2001	Year 2001 YSI continuous water quality data, Fish Brook, Middleton, MA	Vorosmarty	2001	2001	O
WAT-YSI-FishBR-2002	Year 2002 YSI continuous water quality data, Fish Brook, Middleton, MA	Vorosmarty	2002	2002	O
WAT-YSI-Forest-2001	Year 2001 YSI continuous water quality data, Cart Creek, Newbury, MA	Vorosmarty	2001	2001	O
WAT-YSI-Forest-2002	Year 2002 YSI continuous water quality data, Cart Creek, Newbury, MA	Vorosmarty	2002	2002	O
WAT-YSI-Forest-2003	Year 2003 YSI continuous water quality data, Cart Creek, Newbury, MA	Vorosmarty	2003	2003	O
WAT-YSI-Forest-2004	Year 2004 YSI continuous water quality data, Cart Creek, Newbury, MA	Vorosmarty	2004	2004	O
WAT-YSI-Forest-2005	Year 2005 YSI continuous water quality	Vorosmarty	2005	2005	O

Dataset	**Dataset Title**	**Lead PI**	**Begin Year**	**End Year**	**On Line Status**
	data, Cart Creek, Newbury, MA				
WAT-YSI-Forest-2006	Year 2006 YSI continuous water quality data, Cart Creek, Newbury, MA	Vorosmarty	2006	2006	O
WAT-YSI-Forest-2007	Year 2007 YSI continuous water quality data, Cart Creek, Newbury, MA	Vorosmarty	2007	2007	O
WAT-YSI-Forest-2008	Year 2008 YSI continuous water quality data, Cart Creek, Newbury, MA	Wollheim	2008	2008	O
WAT-YSI-Forest-2009	Year 2009 YSI continuous water quality data, Cart Creek, Newbury, MA	Wollheim	2009	2009	O
WAT-YSI-UpperIps-2001	Year 2001 YSI continuous water quality data, Ipswich River, North Reading, MA	Vorosmarty	2001	2001	O
WAT-YSI-UpperIps-2002	Year 2002 YSI continuous water quality data, Ipswich River, North Reading, MA	Vorosmarty	2002	2002	O
WAT-YSI-UpperIps-2003	Year 2003 YSI continuous water quality data, Ipswich River, North Reading, MA	Vorosmarty	2003	2003	O
WAT-YSI-Urban-2001	Year 2001 YSI continuous water quality data, Saw Mill Brook, Burlington, MA	Vorosmarty	2001	2001	O
WAT-YSI-Urban-2002	Year 2002 YSI continuous water quality data, Saw Mill Brook, Burlington, MA	Vorosmarty	2002	2002	O
WAT-YSI-Urban-2003	Year 2003 YSI continuous water quality data, Saw Mill Brook, Burlington, MA	Vorosmarty	2003	2003	O
WAT-YSI-Urban-2004	Year 2004 YSI continuous water quality data, Saw Mill Brook, Burlington, MA	Vorosmarty	2004	2004	O
WAT-YSI-Urban-2005	Year 2005 YSI continuous water quality data, Saw Mill Brook, Burlington, MA	Vorosmarty	2005	2005	O
WAT-YSI-Urban-2006	Year 2006 YSI continuous water quality data, Saw Mill Brook, Burlington, MA	Vorosmarty	2006	2006	O
WAT-YSI-Urban-2007	Year 2007 YSI continuous water quality data, Saw Mill Brook, Burlington, MA	Vorosmarty	2007	2007	P
WAT-YSI-Urban-2008	Year 2008 YSI continuous water quality data, Saw Mill Brook, Burlington, MA	Wollheim	2008	2008	P
WAT-YSI-Urban-2009	Year 2009 YSI continuous water quality data, Saw Mill Brook, Burlington, MA	Wollheim	2009	2009	P
WAT-YSI-Swamp-2005	Year 2005 YSI continuous water quality data, Cedar Swamp, Bear Brook, Reading, MA	Vorosmarty	2005	2005	O
WAT-YSI-Swamp-2006	Year 2006 YSI continuous water quality data, Cedar Swamp, Bear Brook, Reading, MA	Vorosmarty	2006	2006	O
WAT-YSI-Swamp-2007	Year 2007 YSI continuous water quality data, Cedar Swamp, Bear Brook, Reading, MA	Vorosmarty	2007	2007	O
WAT-YSI-Swamp-2008	Year 2008 YSI continuous water quality data, Cedar Swamp, Bear Brook, Reading, MA	Wollheim	2008	2008	O
WAT-YSI-Swamp-2009	Year 2009 YSI continuous water quality data, Cedar Swamp, Bear Brook, Reading, MA	Wollheim	2009	2009	O
MARSH					
MAR-RO-Transects	Marsh vegetation along 5 transects on the	Hopkinson	1998	1998	O

Dataset	**Dataset Title**	**Lead PI**	**Begin Year**	**End Year**	**On Line Status**
	Rowley River				
MAR-RO-Sedimentation	Sedimentation along five transects on the Rowley River	Hopkinson	1998	1998	O
MAR-RO-Marker-Horizon	Marsh sediment marker horizon data from Rowley marshes	Hopkinson	2000	2003	O
MAR-RO-SET	Marsh platform SET data from Rowley marshes	Hopkinson	2002	2007	O
MAR-PR-Porewater	Porewater nutrients, Parker River, MA	Giblin	2004	2009	O
MAR-VA-Porewater	Porewater nutrients (Rowley, Parker Rivers, MA) (Wells, ME)	Morris	1998	2000	O
MAR-PR-Wtable-RRA-2001	Water table heights at the railroad Spartina marsh on Parker River	Hopkinson	2001	2001	O
MAR-PR-Wtable-RRB-2001	Water table heights at the railroad Spartina marsh on Parker River	Hopkinson	2001	2001	O
MAR-PR-Wtable-RRA-2002	Water table heights at the railroad Spartina marsh on Parker River	Hopkinson	2002	2002	O
MAR-PR-Wtable-RRB-2002	Water table heights at the railroad Spartina marsh on Parker River	Hopkinson	2002	2002	O
MAR-PR-Wtable-RR-2003	Water table heights at the railroad Spartina marsh on Parker River	Hopkinson	2003	2003	O
MAR-PR-Wtable-RR-2004	Water table heights at the railroad Spartina marsh on Parker River	Hopkinson	2004	2004	O
MAR-PR-Wtable-RR-2006	Water table heights at the railroad Spartina marsh on Parker River	Hopkinson	2006	2006	O
MAR-PR-Wtable-RR-2007	Water table heights at the railroad Spartina marsh on Parker River	Hopkinson	2007	2007	O
MAR-PR-Wtable-TA-2001	Water table heights in Typha marsh on the Parker River	Hopkinson	2001	2001	O
MAR-PR-Wtable-TB-2001	Water table heights in Typha marsh on the Parker River	Hopkinson	2001	2001	O
MAR-PR-Wtable-TA-2002	Water table heights in Typha marsh on the Parker River	Hopkinson	2002	2002	O
MAR-PR-Wtable-TB-2002	Water table heights in Typha marsh on the Parker River	Hopkinson	2002	2002	O
MAR-PR-Wtable-T-2003	Water table heights in Typha marsh on the Parker River	Hopkinson	2003	2003	O
MAR-PR-Wtable-T-2004	Water table heights in Typha marsh on the Parker River	Hopkinson	2004	2004	O
MAR-PR-Wtable-T-2006	Water table heights in Typha marsh on the Parker River	Hopkinson	2006	2006	O
MAR-PR-Wtable-T-2007	Water table heights in Typha marsh on the Parker River	Hopkinson	2007	2007	O
LTE-MP-LAC-biomassmeans	Biomass, Spartina alterniflora, aboveground, Law’s Point, Rowley River, MA	Morris	1999	2008	O
LTE-MP-LPC-biomassmeans	Biomass, Spartina patens, aboveground, Law’s Point, Rowley River, MA	Morris	2001	2008	O
LTE-MP-NAC-biomassmeans	Biomass, Spartina alterniflora, aboveground, Goat Island, North Inlet, SC	Morris	1984	2008	O

Dataset	**Dataset Title**	**Lead PI**	**Begin Year**	**End Year**	**On Line Status**
LTE-MP-LAC-productivitymeans	Annual productivity, Spartina alterniflora, Law's Point, Rowley River, MA	Morris	1999	2008	O
LTE-MP-LPC-productivitymeans	Annual productivity, Spartina patens, Law's Point, Rowley River, MA	Morris	2001	2008	O
LTE-MP-NAC-productivitymeans	Annual productivity, Spartina alterniflora, Goat Island, North Inlet, SC	Morris	1984	2008	O
LTE-MP-LAC-porewatermeans	Nutrient concentrations from porewater, Spartina alterniflora dominated marsh, Law's Point, Rowley River, MA	Morris	1999	2008	O
LTE-MP-LPC-porewatermeans	Nutrient concentrations from porewater, Spartina patens dominated marsh, Law's Point, Rowley River, MA	Morris	2000	2008	O
LTE-MP-OTC-porewatermeans	Nutrient concentrations from porewater, Typha sp. dominated marsh, Upper Parker River, Newbury, MA	Morris	2000	2008	O
LTE-MP-NAC-porewatermeans	Nutrient concentrations from porewater, Spartina alterniflora dominated marsh, Goat Island, North Inlet, SC	Morris	1994	2008	O
LTE-MP-LAC-elevationmeans	Marsh surface elevation, Spartina alterniflora dominated marsh, Law's Point, Rowley River, MA	Morris	1999	2008	O
LTE-MP-LPC-elevationmeans	Marsh surface elevation, Spartina patens dominated marsh, Law's Point, Rowley River, MA	Morris	2000	2008	O
LTE-MP-NAC-elevationmeans	Marsh surface elevation, Spartina alterniflora dominated marsh, Goat Island, North Inlet, SC	Morris	1996	2008	O
WATER COLUMN					
EST-PR-O2	Parker River Plum Island Sound, dawn & dusk metabolism transects	Hopkinson	1995	2001	O
EST-PR-O2info	Information data file for oxygen dawn & dusk metabolism transect file EST-PR-O2	Hopkinson	1995	2000	O
EST-PR-NUT	Parker River Plum Island Sound, water chemistry transects	Hopkinson	1994	2007	O
EST-PR-ChemTax	Phytoplankton identification using HPLC and Chem Taxonomy, Plum Island Estuary	Hopkinson	2003	2009	O
MON-PR-MBYSI2000	Year 2000 YSI continuous water quality data, Parker River, Middle Rd.	Hopkinson	2000	2000	O
MON-PR-MBYSI2001	Year 2001 YSI continuous water quality data, Parker River, Middle Rd.	Hopkinson	2001	2001	O
MON-PR-MBYSI2002	Year 2002 YSI continuous water quality data, Parker River, Middle Rd.	Hopkinson	2002	2002	O
MON-PR-MBYSI2003	Year 2003 YSI continuous water quality data, Parker River, Middle Rd.	Hopkinson	2003	2003	O
MON-PR-MBYSI2004	Year 2004 YSI continuous water quality data, Parker River, Middle Rd.	Hopkinson	2004	2004	O
MON-PR-MBYSI2005	Year 2005 YSI continuous water quality data, Parker River, Middle Rd.	Hopkinson	2005	2005	O
MON-PR-MBYSI2006	Year 2006 YSI continuous water quality	Hopkinson	2006	2006	O

Dataset	Dataset Title	Lead PI	Begin Year	End Year	On Line Status
	data, Parker River, Middle Rd.				
MON-PR-MBYSI2007	Year 2007 YSI continuous water quality data, Parker River, Middle Rd.	Hopkinson	2007	2007	P
MON-PR-MBYSI2008	Year 2008 YSI continuous water quality data, Parker River, Middle Rd.	Hopkinson	2008	2008	P
MON-PR-MBYSI2009	Year 2009 YSI continuous water quality data, Parker River, Middle Rd.	Hopkinson	2009	2009	P
MON-PR-RT1AYSI2000	Year 2000 YSI continuous water quality data, Parker River, Rt1A	Hopkinson	2000	2000	O
MON-PR-RT1AYSI2001	Year 2001 YSI continuous water quality data, Parker River, Rt1A	Hopkinson	2001	2001	O
MON-PR-RT1AYSI2002	Year 2002 YSI continuous water quality data, Parker River, Rt1A	Hopkinson	2002	2002	O
MON-PR-RT1AYSI2003	Year 2003 YSI continuous water quality data, Parker River, Rt1A	Hopkinson	2003	2003	P
MON-PR-RT1AYSI2004	Year 2004 YSI continuous water quality data, Parker River, Rt1A	Hopkinson	2004	2004	P
MON-PR-RT1AYSI2005	Year 2005 YSI continuous water quality data, Parker River, Rt1A	Hopkinson	2005	2005	P
MON-PR-RT1AYSI2006	Year 2006 YSI continuous water quality data, Parker River, Rt1A	Hopkinson	2006	2006	P
MON-PR-RT1AYSI2007	Year 2007 YSI continuous water quality data, Parker River, Rt1A	Hopkinson	2007	2007	P
MON-SO-IBYCYSI2000	Year 2000 YSI continuous water quality data, Plum Island Sound, IBYC	Hopkinson	2000	2000	O
MON-SO-IBYCYSI2001	Year 2001 YSI continuous water quality data, Plum Island Sound, IBYC	Hopkinson	2001	2001	O
MON-SO-IBYCYSI2002	Year 2002 YSI continuous water quality data, Plum Island Sound, IBYC	Hopkinson	2002	2002	O
MON-SO-IBYCYSI2003	Year 2003 YSI continuous water quality data, Plum Island Sound, IBYC	Hopkinson	2003	2003	O
MON-SO-IBYCYSI2004	Year 2004 YSI continuous water quality data, Plum Island Sound, IBYC	Hopkinson	2004	2004	O
MON-SO-IBYCYSI2005	Year 2005 YSI continuous water quality data, Plum Island Sound, IBYC	Hopkinson	2005	2005	O
MON-SO-IBYCYSI2006	Year 2006 YSI continuous water quality data, Plum Island Sound, IBYC	Hopkinson	2006	2006	O
MON-SO-IBYCYSI2007	Year 2007 YSI continuous water quality data, Plum Island Sound, IBYC	Hopkinson	2007	2007	O
MON-SO-IBYCYSI2008	Year 2008 YSI continuous water quality data, Plum Island Sound, IBYC	Hopkinson	2008	2008	P
MON-SO-IBYCYSI2009	Year 2009 YSI continuous water quality data, Plum Island Sound, IBYC	Hopkinson	2009	2009	P
BENTHOS					
BEN-PR-Flux	Benthic metabolism and nutrient cycling in Parker & Rowley Rivers	Giblin	1993	2009	O
BEN-PR-Sediment	Benthic sediment porewater chemistry in Parker & Rowley Rivers	Giblin	1993	1999	O
HIGHER TROPHIC LEVELS					

Dataset	**Dataset Title**	**Lead PI**	**Begin Year**	**End Year**	**On Line Status**
HTL-PIE-YearlyIsotopeSurvey	Annual stable isotope functional group surveys	Deegan	1999	2008	O
HTL-PIE-Survey-1993	Monthly aquatic macrofauna sampling during 1993	Deegan	1993	1993	O
HTL-PIE-Survey-1994	Monthly aquatic macrofauna sampling during 1994	Deegan	1994	1994	O
HTL-PIE-Survey-1997	Monthly aquatic macrofauna sampling during 1997	Deegan	1997	1997	O
HTL-PIE-Survey-1998	Monthly aquatic macrofauna sampling during 1998	Deegan	1998	1998	O
HTL-PIE-Survey-1999	Monthly aquatic macrofauna sampling during 1999	Deegan	1999	1999	O
HTL-PIE-Survey-2002	Monthly aquatic macrofauna sampling during 2002	Deegan	2002	2002	O
HTL-PR-Isotope	Stable isotope survey of aquatic macrofauna in Plum Island Estuary	Deegan	1993	1994	O
HTL-SO-Bird	Decade average counts for selected birds in Plum Island Sound	Buchsbaum	1930	1999	O
HTL-MAR-BreedingBirds	Surveys of salt marsh breeding birds using point counts	Buchsbaum	2004	2008	O
MON-EX-PRNWR-Breeding-Birds	Breeding bird census data at the Parker River National Wildlife Refuge	Buchsbaum	1994	2002	O
MON-EX-PRNWR-Salt-Marsh-Birds	Salt marsh bird census data at the Parker River National Wildlife Refuge	Buchsbaum	1999	2001	O
MON-EX-PRNWR-Volunteer-Birds	Bird observations by volunteers at the Parker River National Wildlife Refuge	Buchsbaum	1194	2002	O
LONG TERM EXPERIMENTS					
LTE-MP-SET-means	Summarized sediment elevation table data from marsh fertilized plots	Morris	1999	2009	O
LTE-MP-SET-raw	Raw sediment elevation table data from marsh fertilized plots	Morris	1999	2009	O
LTE-MP-NIN-elevationmeans	Marsh surface elevation data at a *Spartina alterniflora*-dominated salt marsh at Goat Island, North Inlet, Georgetown, SC.	Morris	1996	2009	O
LTE-MP-LPP-biomass	Vegetation biomass from Spartina patens marsh fertilized plots	Morris	2000	2009	O
LTE-MP-LPA-biomass	Vegetation biomass from Spartina alterniflora marsh fertilized plots	Morris	1999	2009	O
LTE-MP-ORT-biomass	Biomass measurements of *Typha* sp. at Upper Parker River brackish marsh site.	Morris	2002	2008	O
LTE-MP-NIN-biomass	Aboveground biomass data from a *Spartina alterniflora*-dominated salt marsh plots in North Inlet, Georgetown, SC.	Morris	1984	2009	O
LTE-MP-LPA-productivity	Annual productivity at *Spartina alterniflora*-dominated salt marsh plots at Law’s Point, Rowley, MA	Morris	1999	2009	O
LTE-MP-NIN-productivity	Annual productivity at *Spartina alterniflora*-dominated salt marsh plots in North Inlet, Georgetown, SC.	Morris	1985	2009	O

Dataset	**Dataset Title**	**Lead PI**	**Begin Year**	**End Year**	**On Line Status**
LTE-MP-porewater	Nutrient concentrations from porewater samples at three marsh fertilization experimental research sites in the low marsh (*Spartina alterniflora* dominated) and high marsh (*Spartina patens* dominated) at Law's Point and on the upper Parker River (*Typha sp.* dominated marsh).	Morris	1999	2009	O
LTE-MP-NIN-porewater	Nutrient concentrations from porewater samples at *Spartina alterniflora*-dominated salt marsh plots in North Inlet, Georgetown, SC.	Morris	1993	2009	O
LTE-TC-NUT	Pre-fertilization water-column nutrients in tidal creeks	Deegan	1998	2001	O
LTE-TC-BenChl	Pre-fertilization benthic chlorophyll concentration in tidal creeks	Deegan	1998	2002	O
LTE-TC-GreenwoodIsotopes	Stable isotopes of organisms in Greenwood Creek	Deegan	2001	2001	O
LTE-MD-VEGSTN	Physical layout of sites in hayed and reference areas	Buchsbaum	2000	2000	O
LTE-MD-VEGTRANS	Plant species presence in hayed and control areas	Buchsbaum	2000	2001	O
LTE-MD-VEGQUADS	Vegetation cover in hayed and control areas	Buchsbaum	2000	2001	O
LTE-MD-EARLYVEG	Vegetation biomass & shoot densities at hayed and reference sites	Buchsbaum	2000	2000	O
LTE-MD-EOYBIOMASS	Vegetation biomass & cover, end of season at hayed and reference sites	Buchsbaum	2000	2001	O
LTE-MD-BIRD-HAY-STN	List of stations used for bird counts in hayed and reference sites	Buchsbaum	2000	2000	O
LTE-MD-BIRD-HAY-DATA	Bird observations in newly hayed and adjacent reference sites	Buchsbaum	2000	2001	O
LTE-MF-GREENWOOD-CLUBHEAD-VEGST	Vegetation transect physical layout at the enriched and reference sites	Buchsbaum	2002	2002	O
LTE-MF-GREENWOOD-CLUBHEAD- VEGQD	Plant species percent cover at enriched and reference sites	Buchsbaum	2002	2002	O
LTE-MF-GREENWOOD-CLUBHEAD-EOY-BM	Vegetation biomass & cover, end of season at enriched and reference sites	Buchsbaum	2002	2002	O
LTE-MF-GREENWOOD-CLUBHEAD-VEGTR	Vegetation presence or absence at enriched and reference sites	Buchsbaum	2002	2002	O
LTE-EX-ARGILLA-RM-VEGSTN	Vegetation transect physical layout on Argilla Rd and Rough Meadows	Buchsbaum	1995	2002	O
LTE-EX-ARGILLA-RM-VEGQUADS	Plant species percent cover at Argilla Rd and Rough Meadows marshes	Buchsbaum	1999	2002	O
LTE-EX-ARGILLA-RM-VEGTRANS	Plant species presence in Argilla Rd and Rough Meadows marsh	Buchsbaum	1995	2002	O
LTE-EX-ARGILLA-RM-PHRAGHEIGHTS	Phragmites heights at Argilla Rd and Rough Meadows marshes	Buchsbaum	1997	2002	O
SHORT TERM EXPERIMENTS					
STP-PR-Mesocosm	Mesocosm experiment testing quality &	Hopkinson	1994	1994	O

Dataset	Dataset Title	Lead PI	Begin Year	End Year	On Line Status
	quantity of DOM on foodwebs				
PHY-PR-SF6	SF6 addition concentration gradients and wind speed in Parker River	Hopkinson	1996	1996	O
STP-PR-Nisotrex1	Baseline stable isotopes during Nisotrex1	Peterson	1995	1996	P
STP-RO-Nisotrex2	Baseline stable isotopes during Nisotrex2	Peterson	2000	2000	P
SCHOOLYARD					
MON-PR-GDATrans1Middle2000	GDA Parker River Middle Rd. vegetation transect #1 during year 2000	Buchsbaum	2000	2000	O
MON-PR-GDATrans2Middle2000	GDA Parker River Middle Rd. vegetation transect #2 during year 2000	Buchsbaum	2000	2000	O
MON-PR-GDATrans3Middle2000	GDA Parker River Middle Rd. vegetation transect #3 during year 2000	Buchsbaum	2000	2000	O
MON-PR-GDATrans4Middle2000	GDA Parker River Middle Rd. vegetation transect #4 during year 2000	Buchsbaum	2000	2000	O
MON-PR-GDATrans5Middle2000	GDA Parker River Middle Rd. vegetation transect #5 during year 2000	Buchsbaum	2000	2000	O
MON-PR-GDATrans6Middle2000	GDA Parker River Middle Rd. vegetation transect #6 during year 2000	Buchsbaum	2000	2000	O
MON-PR-GDATrans7Middle2000	GDA Parker River Middle Rd. vegetation transect #7 during year 2000	Buchsbaum	2000	2000	O
MON-PR-GDATrans8AMiddle2000	GDA Parker River Middle Rd. vegetation transect #8A during year 2000	Buchsbaum	2000	2000	O
MON-PR-GDATrans8BMiddle2000	GDA Parker River Middle Rd. vegetation transect #8B during year 2000	Buchsbaum	2000	2000	O
MON-PR-GDATrans2Middle2002	GDA Parker River Middle Rd. vegetation transect #2 during year 2002	Buchsbaum	2002	2002	O
MON-PR-GDATrans3Middle2002	GDA Parker River Middle Rd. vegetation transect #3 during year 2002	Buchsbaum	2002	2002	O
MON-RO-GDAMusselSnail1999	GDA mussel and snail presence in Rowley River tidal creeks during 1999	Deegan	1999	1999	O
MON-RO-GDAMusselSnail2000	GDA mussel and snail presence in Rowley River tidal creeks during 2000	Deegan	2000	2000	O
MON-RO-GDAMusselSnail2001	GDA mussel and snail presence in Rowley River tidal creeks during 2001	Deegan	2001	2001	O
MON-RO-GDAMusselSnail2002	GDA mussel and snail presence in Rowley River tidal creeks during 2002	Deegan	2002	2002	O
MON-VA-MassAudSaltMarsh	Mass Audubon salt marsh science transects	Buchsbaum			P
CLIMATE					
MON-PR-Met15min2000	Year 2000, continuous 15 minute averages of meteorological station data	Hopkinson	2000	2000	O
MON-PR-Met15min2001	Year 2001, continuous 15 minute averages of meteorological station data	Hopkinson	2001	2001	O
MON-PR-Met15min2002	Year 2002, continuous 15 minute averages of meteorological station data	Hopkinson	2002	2002	O
MON-PR-Met15min2003	Year 2003, continuous 15 minute averages of meteorological station data	Hopkinson	2003	2003	O
MON-PR-Met15min2004	Year 2004, continuous 15 minute averages of meteorological station data	Hopkinson	2004	2004	O

Dataset	Dataset Title	Lead PI	Begin Year	End Year	On Line Status
MON-PR-Met15min2005	Year 2005, continuous 15 minute averages of meteorological station data	Hopkinson	2005	2005	O
MON-PR-Met15min2006	Year 2006, continuous 15 minute averages of meteorological station data	Hopkinson	2006	2006	O
MON-PR-Met15min2007	Year 2007, continuous 15 minute averages of meteorological station data	Hopkinson	2007	2007	O
MON-PR-Met15min2008	Year 2008, continuous 15 minute averages of meteorological station data	Hopkinson	2008	2008	O
MON-PR-Met15min2009	Year 2009, continuous 15 minute averages of meteorological station data	Hopkinson	2009	2009	P
MON-PR-MetHour2000	Year 2000, hourly averages of meteorological station data	Hopkinson	2000	2000	O
MON-PR-MetHour2001	Year 2001, hourly averages of meteorological station data	Hopkinson	2001	2001	O
MON-PR-MetHour2002	Year 2002, hourly averages of meteorological station data	Hopkinson	2002	2002	O
MON-PR-MetDay	Daily averages of meteorological station data	Hopkinson	2000	2008	O
MON-VA-NCDC	Climate data from National Climate Data Center	Hopkinson			P
ESTUARINE PHYSICS					
PHY-PR-Dimensions	Physical dimensions of the Parker River channel	Vallino	1993	1996	O
PHY-PR-DYE	Rhodamine dye additions to Parker River	Hopkinson	1993	1996	O
PHY-PR-SF6	SF6 additions to Parker River	Hopkinson	1996	1996	O
MON-BO-Sealevel-Monthly-MSL	Monthly mean sea level (1921-2009) Boston, MA, NOAA/NOS	Hopkinson	1921	2009	O
MON-PR-MBWatLevel2000	Year 2000, water level data, Middle Road Bridge, Parker River	Vallino	2000	2000	O
MON-PR-MBWatLevel2001	Year 2001, water level data, Middle Road Bridge, Parker River	Vallino	2001	2001	O
MON-PR-MBWatLevel2002	Year 2002, water level data, Middle Road Bridge, Parker River	Vallino	2002	2002	O
MON-PR-MBWatLevel2003	Year 2003, water level data, Middle Road Bridge, Parker River	Vallino	2003	2003	P
MON-PR-MBWatLevel2004	Year 2004, water level data, Middle Road Bridge, Parker River	Vallino	2004	2004	P
MON-PR-MBWatLevel2005	Year 2005, water level data, Middle Road Bridge, Parker River	Vallino	2005	2005	P
MON-PR-MBWatLevel2006	Year 2006, water level data, Middle Road Bridge, Parker River	Vallino	2006	2006	P
MON-PR-MBWatLevel2007	Year 2007, water level data, Middle Road Bridge, Parker River	Vallino	2007	2007	P
MON-PR-MBWatLevel2008	Year 2008, water level data, Middle Road Bridge, Parker River	Vallino	2008	2008	P
MON-PR-MBWatLevel2009	Year 2009, water level data, Middle Road Bridge, Parker River	Vallino	2009	2009	P
MON-PR-RT1AWatLevel2000	Year 2000, water level data, Rt 1A, Parker River	Vallino	2000	2000	O

Dataset	Dataset Title	Lead PI	Begin Year	End Year	On Line Status
MON-PR-RT1AWatLevel2001	Year 2001, water level data, Rt 1A, Parker River	Vallino	2001	2001	O
MON-PR-RT1AWatLevel2002	Year 2002, water level data, Rt 1A, Parker River	Vallino	2002	2002	O
MON-PR-RT1AWatLevel2003	Year 2003, water level data, Rt 1A, Parker River	Vallino	2003	2003	P
MON-PR-RT1AWatLevel2004	Year 2004, water level data, Rt 1A, Parker River	Vallino	2004	2004	P
MON-PR-RT1AWatLevel2005	Year 2005, water level data, Rt 1A, Parker River	Vallino	2005	2005	P
MON-PR-RT1AWatLevel2006	Year 2006, water level data, Rt 1A, Parker River	Vallino	2006	2006	P
MON-SO-IBYCWatLevel2000	Year 2000, water level data, Ipswich Bay Yacht Club, Plum Island Sound	Vallino	2000	2000	O
MON-SO-IBYCWatLevel2001	Year 2001, water level data, Ipswich Bay Yacht Club, Plum Island Sound	Vallino	2001	2001	O
MON-SO-IBYCWatLevel2002	Year 2002, water level data, Ipswich Bay Yacht Club, Plum Island Sound	Vallino	2002	2002	O
MON-SO-IBYCWatLevel2003	Year 2003, water level data, Ipswich Bay Yacht Club, Plum Island Sound	Vallino	2003	2003	P
MON-SO-IBYCWatLevel2004	Year 2004, water level data, Ipswich Bay Yacht Club, Plum Island Sound	Vallino	2004	2004	P
MON-SO-IBYCWatLevel2005	Year 2005, water level data, Ipswich Bay Yacht Club, Plum Island Sound	Vallino	2005	2005	P
MON-SO-IBYCWatLevel2006	Year 2006, water level data, Ipswich Bay Yacht Club, Plum Island Sound	Vallino	2006	2006	P
MON-SO-IBYCWatLevel2007	Year 2007, water level data, Ipswich Bay Yacht Club, Plum Island Sound	Vallino	2007	2007	P
MON-SO-IBYCWatLevel2008	Year 2008, water level data, Ipswich Bay Yacht Club, Plum Island Sound	Vallino	2008	2008	P
MON-SO-IBYCWatLevel2009	Year 2009, water level data, Ipswich Bay Yacht Club, Plum Island Sound	Vallino	2009	2009	P
GLOBAL POSITIONING					
GPS-VA-Kinematic	Trimble GPS Kinematic surveys	Vallino	1998	2009	P
GPS-VA-Static	Trimble GPS Static surveys	Vallino	1998	2009	P
GIS & MAPS					
GIS-VA-PIEGIS	Longitude and latitude of various PIE-LTER sampling sites	Hopkinson	1994	2009	O
GIS-IP-ip30_info_anderson	Ipswich watershed land use 1971, 1985, 1991, 1999 according to MassGIS and Anderson Level 1	Pontius	1971	1999	O
GIS-IP-ip30_info_aspect	Ipswich Watershed aspect model.	Pontius	2002	2002	O
GIS-IP-ip30_info_dem	Ipswich Watershed Digital Elevation Model using 30m grid.	Pontius	2002	2002	O
GIS-IP-ip30_info_hydrology	Ipswich Watershed hydrology map to be used to generate a hydrologically corrected Digital Elevation Model.	Pontius	2002	2002	O
GIS-IP-ip30_info_nutrientsamplesites	Ipswich Watershed single pixel locations of nutrient sampling sites in the Ipswich	Pontius	1999	1999	O

Dataset	**Dataset Title**	**Lead PI**	**Begin Year**	**End Year**	**On Line Status**
	River Watershed.				
GIS-IP-ip30_info_open_protection	Ipswich Watershed areas defined as protected and recreational open space.	Pontius	2002	2002	O
GIS-IP-ip30_info_open_purpose	Primary use of Ipswich Watershed areas defined as protected and recreational open space.	Pontius	2002	2002	O
GIS-IP-ip30_open_status	Status of Ipswich Watershed areas defined as protected and recreational open space.	Pontius	2002	2002	O
GIS-IP-ip30_info_roads	Ipswich Watershed roads taken from MassGIS.	Pontius	2002	2002	O
GIS-IP-ip30_info_slope	Ipswich Watershed slope model generated from Digital Elevation Model.	Pontius	2002	2002	O
GIS-IP-ip30_info_townmask	Shows the entirety of towns that have area within the Ipswich River Watershed..	Pontius	2001	2001	O
GIS-IP-ip30_info_towns	Shows the areas of towns that are located within the Ipswich River Watershed.	Pontius	2001	2001	O
GIS-IP-ip30_info_townsvector	Shows the areas of towns that are located within the Ipswich River Watershed, vector form.	Pontius	2001	2001	O
GIS-IP-ip30_info_wetlands	Shows locations of wetlands within the Ipswich study area.	Pontius	2001	2001	O
GIS-IP-ip30_info_window	This map shows the extent of the Ipswich River Watershed study area.	Pontius	2001	2001	O
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	O
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	O
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	O
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	O
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	O
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	O
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	O

Dataset	**Dataset Title**	**Lead PI**	**Begin Year**	**End Year**	**On Line Status**
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	O
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	O
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	O
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	O
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	O
GIS-p_mask_01	Plum Island Ecosystems Mask (Idrisi raster)	Pontius	1999	1999	O
GIS-p_mask_vector_01	Plum Island Ecosystems Mask (Idrisi raster)	Pontius	1999	1999	O
GIS-p_towns_01	Plum Island Ecosystems Towns (Idrisi raster)	Pontius	1999	1999	O
GIS-p_towns_vector_01	Plum Island Ecosystems Towns (Idrisi raster)	Pontius	1999	1999	O
GIS-p_watersheds_01	Plum Island Ecosystems Watersheds (Idrisi raster)	Pontius	2000	2000	O
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	O
WAT-RGIS-120m-FlowDirection	Gridded flow direction (i.e. river network) of the watersheds draining to Plum Island Sound	Wollheim	2007	2007	O
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	O
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	O
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	O
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	O