

## 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. The principal study site is the Plum Island Sound estuary, its coupled Parker, Rowley and Ipswich River watersheds and the adjacent coastal ocean, the Gulf of Maine. Humans are altering the ecosystems of the world at rates not previously experienced. Understanding and predicting how multiple stresses affect the sustainability of ecosystems is one of the most crucial challenges in environmental biology. The PIE LTER focuses on how several aspects of global change influence organic matter and inorganic nutrient biogeochemistry and estuarine foodwebs. The inputs of organic matter and nutrients from land, ocean and marshes interact with the external drivers (climate, land use, river discharge, sea level) to dictate the extent and degree of nutrient and organic matter processing and determine the spatial patterns of estuarine productivity and trophic structure. The overarching question is:

**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?**

The project uses a combination of approaches to address research questions and hypotheses: 1) short- and long-term “core” measurements 2) short and long-term experiments, 3) comparative ecosystem studies and 4) modeling. The research integrates estuarine biogeochemistry with studies of food webs and population biology of all trophic levels. The PIE LTER data and information system provides a centralized network of information and data related to the Plum Island Sound Estuarine Ecosystem and its watersheds. The 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 easily accessible to PIE-LTER scientists, local, regional, 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.

**Broader Impacts:** PIE-LTER has developed links with local teachers and students, citizens, conservation organizations, and local, state and federal agencies. What started out as a “minimalist” program has grown to be a broad, well-rounded suite of activities. The education/outreach program is expected to further expand during LTER2, as additional support is obtained from other federal agencies, the Commonwealth of Massachusetts, and private foundations. The long-term goal is to establish a ‘Coastal Outreach’ office at the PIE-LTER study site that will serve to integrate and promote interactions with interested parties throughout New England. During the next funding cycle, the LTER will expand its schoolyard program to provide on-going professional development for teachers; support the expansion of this project into nearby urban areas including Salem, Boston, and Revere; and facilitate the transfer of this program to New Hampshire and Maine via the Gulf of Maine Institute. There will have greater involvement with undergraduate and graduate education with the addition of PIs Mather and Pontius from UMass and Clark University. PIE-LTER has a very active outreach program in which the goal is to communicate research findings to individuals, organizations, and agencies that will use PIE-LTER research results to better manage local and regional coastal resources. The project has established partnerships on three major issues: intertidal marshes, coastal eutrophication and watershed resource management. The issues of sea level rise, marsh survival and wetland restoration will be the next outreach focal points of the project.

## SECTION 1: RESULTS FROM PRIOR SUPPORT

### Plum Island Sound Comparative Ecosystems Study

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The Plum Island Ecosystems LTER (PIE LTER) was established in 1998. Over the past 5-½ years, we have designed and implemented a comprehensive study of a major, land-estuarine system in the Acadian biogeographic province in eastern New England. Our goal is to develop a predictive understanding of the long-term dynamics of watershed and estuarine ecosystems at the land-sea interface and to apply this knowledge to the wise management and development of policy to protect the natural resources of the coastal zone. The principal study site is the Plum Island Sound estuary, its coupled Parker and Ipswich River basins and the coastal ocean, the Gulf of Maine.

Research at the site has involved 232 individuals from 74 research and education institutions. A total of 118 publications, including 20 dissertations and theses, have resulted from LTER research since 1998 (Table 1.1-Suppl Docs). Scientists and students are attracted to this site because of its physical and socioeconomic attributes, including macro-tidal range, size (largest salt marsh estuary in northeast), peat accumulation, biogeographic province, and metropolitan setting. It represents a northern end-member of a gradient in temperature and species composition. Field station facilities, extensive database and long-term experiments provide a framework for comparative studies.

During this first funding cycle, we developed a foundation of research that includes long-term field experiments and measurements in watersheds, atmosphere, intertidal marshes, estuary and coastal ocean. Experiments and observations examine LTER core areas: primary production, organic matter accumulation, nutrient cycling, higher trophic levels, and ecosystem disturbance. Development of data and information management systems to support research, education and outreach activities is an important ongoing activity.

Below we describe *selected* research, education, outreach and information management accomplishments of our LTER program. Our overarching question asks how trophic structure and primary and secondary productivity in estuaries are affected by changes in organic matter and nutrient loading, and hydrodynamics caused by changing land use, climate and sea level. To facilitate presentation, our program is described in 5 research areas plus synthesis: watersheds, tidal marshes, planktonic system, benthos, and higher trophic levels. The hydrologic cycle has emerged as a theme that cuts across each program area and that became increasingly important as we began to synthesize our knowledge about how this ecosystem is coupled and works. We use examples that illustrate the importance of the *hydrologic cycle and hydrodynamics theme*, to illustrate our progress to date and to set the stage for future directions.

**WATERSHED HYDROLOGIC CYCLE** - Following substantial changes in land use in the Ipswich and Parker River watersheds during the 20<sup>th</sup> century (from >50% agriculture in 1900, to > 85% forest in 1950, to >35% urban in 2000) (Pontius and Schneider 2001), we were surprised to find that discharge was largely unchanged. We expected to see increases in discharge due to the increase in impervious surface and a projected decrease in evapotranspiration (ET) associated with land use change from forest to urban (Claessens et al. submitted). Instead we found that diversions and climate change decreased the percentage of rainfall exported from the watershed in rivers.

Analysis of historic climate data shows that precipitation and ET increased 19% and 25% (rates of 2.9 mm and 1.6 mm per year, respectively) between 1931 and 1998 (Claessens et al. submitted). We attribute the discrepancy between expected reduction in ET and actual increase in ET to climate change. We observed a downward trend in minimum temperature beginning in the 1950s as well as an increase in dewpoint temperature and a convergence of minimum and dewpoint temperatures. This pattern is an indication that the near-surface atmosphere has become more humid, a result of increased ET.

Diversions of water for municipal use (drinking water and sewage) has had the greatest impact on hydrologic budgets (Canfield et al. 1999). Diversions today are roughly 20% of annual streamflow. Historically populations outside watershed boundaries have withdrawn water from the Ipswich and Parker rivers for drinking water. More recently water is diverted as sewage to treatment plants outside watershed boundaries. As urban density increases, septic treatment decreases and sewage export increases.

Watershed hydrologic modifications have altered biogeochemical cycles. For instance, N export in sewage is now a major component of the watershed N cycle (Williams et al. submitted a,b). The increased importance of surface flow in urban vs. forested areas leads to reduced contact with “biogeochemically active sites” and a greater input of constituents to streams (Pellerin et al. in prep, Wollheim et al. submitted). We also find that N retention declines in urban areas due to the increased runoff associated with impervious surfaces (Wollheim et al. submitted).

**ESTUARINE HYDRODYNAMICS** – Estuarine hydrodynamics and characteristic mixing times are the result of river runoff, location of river runoff, estuarine geometry and tidal mixing (Vallino and Hopkinson 1998). Total average annual river discharge from the 610-km<sup>2</sup> watershed is 11 m<sup>3</sup> s<sup>-1</sup>, ranging from <0.001 up to 100 m<sup>3</sup> s<sup>-1</sup>. Average discharge is about 67 times lower in volume than a single tidal prism (tidal cycle  $\Delta t$ ). It is the balance between discharge (advection) and tides (dispersion) that controls mixing along the length of the estuary (24 km). Mixing is dominated by dispersion in the lower 10 km of the estuary (Plum Island Sound proper), while advection becomes increasingly important up estuary and as discharge increases. Interestingly the Parker River, which represents only 3% of total discharge, is the major control on estuarine advection because it enters at the head of the estuary. The Ipswich River represents 90% of discharge but enters near the estuary mouth and does not interact with most of the length of the estuary.

As a result of seasonal variations in discharge, there are strong salinity gradients within the estuary that vary over time. During high flow, salinity drops to 0 ppt in the upper 10 km while during low flow salinity can exceed 15 ppt at the very head of the estuary. Likewise there are strong gradients in water residence times along the length of the estuary that also vary in response to river discharge. During low flow (<0.1 m<sup>3</sup> s<sup>-1</sup>) residence time is about 2 weeks in the upper estuary and less than a day in the lower estuary. With increasing discharge residence time decreases throughout the estuary and the region of longest residence time shifts downstream.

Additional factors controlling estuarine hydrology and hydrodynamics are local precipitation (especially during summer when ET is high and river discharge is low) and sea level variation. Mean sea level exhibits strong lunar, seasonal and annual cycles and variability. The effect of sea level variation is to alter tidal excursion lengths and marsh flooding depth and frequency.

Direct precipitation becomes an increasingly important factor controlling salinity distribution, especially on the intertidal marsh in periods of low river discharge and low mean sea level when marsh flooding is limited or absent.

**MARSHES** – The productivity of intertidal marsh plants is strongly related to variations in salinity during the growing season (Morris and Haskin 1990, Morris 2000, Morris et al. 2002). The uptake of nitrogen by salt marsh vegetation is highly inefficient, varies with salinity and MSL, and contributes to the leaky behavior of the saltmarsh nitrogen cycle. The salt gradient moves in response to changes in freshwater discharge and sea level, and this can affect the export and import of ammonium in marshes along the salinity gradient (Koop-Jakobsen and Giblin 2002). As salinity declines upriver, species composition changes (Odum 1988) and the plant community shift to one limited by phosphorus (Daoust and Morris 2003).

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. We have observed substantial marsh disintegration 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 at PIE and reduced sediment loads as a consequence of reforestation of the watershed following abandonment of agriculture in New England. Disintegration results in an increase in total length of the marsh-water interface (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 (Wright et al. 1987, Raymond and Hopkinson 2003).

**PLANKTONIC SYSTEM** – Variations in water residence time along the estuary play a major role in phytoplankton bloom occurrence (Holmes et al. 2000), the relative importance of pelagic and benthic primary production (Hughes et al. 2000), and bacterial community structure (Crump et al. in press). Phytoplankton blooms only occur in the oligohaline part of the estuary during midsummer when river discharge is low and residence time is greater than a week. Blooms also occur offshore during spring and advect into the estuary. Shifts in bacterioplankton community composition along the salinity gradient are related to residence time and bacterial community doubling time in spring, summer and fall seasons. Freshwater and marine populations advected into the estuary represent a large fraction of the bacterioplankton community in all seasons. However, a unique estuarine community forms at intermediate salinities in summer and fall when bacteria doubling time is much shorter than water residence time (Crump et al. in press). The mid-estuary is a region of high heterotrophic activity, with O<sub>2</sub> levels occasionally less than 50% of saturation. This reflects large inputs of organic matter substrates from adjacent intertidal marshes (Raymond and Hopkinson, 2003) that are linked via fluctuations in mean sea level and marsh flooding frequency (Wright et al. 1987). Organic matter inputs from marsh porewater drainage are likely to be 10x greater than those from the rivers.

**ESTUARINE BENTHOS** – Watershed discharge-related spatial and temporal patterns of salinity are important controls of benthic N dynamics (Giblin et al. in prep, Weston et al. in prep) and hence productivity of the overlying water. In spring, when river discharge is high, salinity in the porewaters is low and the majority of the N remineralized in sediments is either held on exchange surfaces, or lost via denitrification. Salinity increases during the summer as discharge decreases and NH<sub>4</sub><sup>+</sup> is displaced from the exchange complex leading to a large benthic flux of NH<sub>4</sub><sup>+</sup> to the water column. This flux appears to be the major source of N supporting the mid-summer phytoplankton bloom in the oligohaline portion of the estuary. In

addition,  $N_2$  losses decrease during summer as both coupled and direct denitrification rates reach minimal values in spite of high N mineralization rates.  $N_2$  losses are suppressed because nitrifiers appear to be unable to adapt to the rapid seasonal change in salinity, shutting off coupled nitrification / denitrification (Mondrup 2000) and because during mid-summer the process of dissimilatory nitrate reduction to ammonium (DNRA) appears to out compete denitrification for  $NO_3^-$  from the water column and water column  $NO_3^-$  concentration is low. In autumn, when the porewater salinities decrease, denitrification rates increase and  $NH_4^+$  fluxes decrease. Preliminary work in intertidal vegetated sediments has also shown the importance of salinity in modulating the release of  $NH_4^+$  (Koop-Jakobsen 2003) and measurements of denitrification are underway.

**ESTUARINE HIGHER TROPHIC LEVELS** – We have also found variations in river discharge and sea level to play a large role in the production of higher trophic levels. Abundance of the dominant marsh fish, mummichog, is positively related to the amount of flooded marsh in creek watersheds (Komorow et al. 1999). Factors affecting habitat quality for fish include marsh area, marsh edge length, flooding frequency, depth and duration and salinity (Haas and Deegan, in prep.). Each of these factors is directly related to sea level and/or river discharge. The species present, as well as their abundance, are related to water residence time, which sets a template that determines the pathways and fate of nitrogen in estuarine systems (Hughes et al. 2000, Holmes et al. 2000, Tobias et al. 2003a, b, Hughes et al., in prep.). When residence time is long, phytoplankton dominate nitrogen uptake and the food web has well developed benthic and pelagic communities with strong benthic-pelagic coupling controlled by the animal community. When water residence time is short, benthic microalgae are the dominant primary producers and the principal food chain is benthic.

**SYNTHESIS** – N export from watersheds is increasing as urbanization proceeds. The timing of N export is largely driven by variations in river discharge. Climate and land use change, as well as water diversions, are causing a greater percentage of river N export to occur earlier in the spring. Interestingly the timing of maximum N export from the watershed is also the time of minimum estuarine residence time and suggesting that the majority of N exported from watersheds is passed directly to the coastal ocean without significant estuarine processing. The greatest N processing occurs in midsummer, when residence time is longest, but when N imports are least. We presently do not know how much of the N during high flow is retained in the estuary and released later in the year. Nor do we know what the potential mechanisms of N retention might be during the high discharge period. Interestingly, the N exported from many watersheds during late winter/early spring fuels a major plankton bloom in coastal waters of the Gulf of Maine, some of which is tidally mixed into estuarine waters. Thus high algal biomass in the lower Plum Island estuary is not produced locally but externally by N not retained during estuarine passage and by oceanic N sources. The major effect of the watershed on this estuarine system appears to be the influence of freshwater discharge on the spatial and temporal pattern of water residence time. Residence time and estuarine geomorphology define the template upon which ecological processes and foodwebs operate.

### **Cross-Site science and network activities**

We organized and hosted several major cross-site and synthesis conferences and workshops: a conference on estuarine synthesis (Hobbie 2000), an LTER Aquatic Science Conference on Cross-site Research in 2000 in Salt Lake City and the LTER CC Science Symposium on Hydrologic Linkages in 2002. PIE scientists presented overview talks during Executive

Committee meetings at NSF in 2002 and 2003. Grad student Rob Daoust serves as student representative to the LTER coordinating committee. Morris has led the intersite comparison of organic matter preservation and we have participated in several others including those led by Newell (GCE), Pennings (GCE) and Blum (VCR). Peterson has been playing a major role in the LINX II intersite comparison of stream N dynamics. We took an active role in the 2000 and 2003 LTER ASMs with Giblin delivering a plenary talk in Seattle. We are also participating in NCEAS synthesis activities including one on Ecosystem Services led by Farber and Costanza. Vallino participated in the 1998 network-sponsored workshop on utilizing supercomputers in ecological modeling. Hobbie organized the series of Bioscience articles for the LTER 20-yr review. Hobbie and Hopkinson serve on advisory committees for the Palmer and Georgia LTERs, and Morris for the EPA's STAR Gulf of Mexico project. Finally, PIs and students have been involved in several International LTER (ILTER) initiatives.

### **LTER data and their management**

We collect, organize and analyze short and long-term datasets on the physical, chemical and biological properties and processes of Plum Island Sound and watersheds, as well as other sites where comparative research is conducted. All the data are available electronically to LTER scientists and collaborators as soon as posted. A list of LTER datasets and their documented on-line use is shown in Table 1.2 (Supplementary Documentation). A description of our information management is described in Section 4.

### **Development of human resources and outreach**

PIE LTER has developed substantial education and outreach programs, notwithstanding the fact that MBL is not a degree-granting institution. Our education program consists of Schoolyard, Undergraduate, Graduate and Post-Graduate components. Our schoolyard program alone involves about 1500 students and 42 teachers in the present school year. Our strategies at the undergraduate level include a) summer research internships (4-7/yr), b) developing a new, LTER-based curriculum (for an MBL undergraduate Semester in Environmental Science, as well as at Clark, UNH and USC), c) undergraduate research projects and senior theses, d) guest lectures and LTER sponsored field trips, and e) research experiences / collaborations for college faculty (see Section 5). Graduate students from UMass, Clark University, UNH and USC have been active LTER participants. We have also hosted several foreign graduate students: 2 Denmark, 2 Portugal.

Outreach is also another major PIE LTER activity. Our goals are to communicate our findings to individuals, organizations, and agencies that could benefit from the knowledge we gain about ecosystems at the land-sea interface, especially as this knowledge could be applied to wise management of local and regional resources. We have established partnerships, collaborations and lines of communication to deal with three major categories of societal issues: intertidal marshes, coastal eutrophication and watershed resource management (see Section 5 and Table 5.1).

## SECTION 2: PROPOSED RESEARCH

### INTRODUCTION and CONCEPTUAL FRAMEWORK

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. The principal study site is the Plum Island Sound estuary, its coupled Parker, Rowley and Ipswich River watersheds and the adjacent coastal ocean, the Gulf of Maine. Our interests are not just local; we extend our understandings to other coastal systems through comparative studies and modeling.

Ecosystems at the land-sea interface play a major but poorly understood role in regional as well as global hydrologic, sediment, and biogeochemical cycles (Hedges et al. 1997, Aller 1998, Blair et al. 2003, McKee 2003). Coastal ecosystems play a key role in the transformation, transport, burial and exchange of water and organic and inorganic carbon and nitrogen between land, atmosphere and the ocean. With an overwhelming majority of the human population living in the coastal zone and with runoff from entire continents funneling through estuaries and ocean margins, coastal systems are among the most heavily impacted ecosystems on the globe.

The biosphere is undergoing unprecedented change as a result of human activities. Major global issues include growth of the human population, land use change, climate change, altered hydrologic cycles, and sea level rise. These are also important issues at regional scales, as well as at the PIE LTER. Human population in the U.S. continues to increase, especially in the coastal zone; we see similar dramatic increases in population in the Ipswich and Parker River watersheds (Fig 2.1). Land use has changed substantially along the entire east coast of the U.S. over the past century. The pattern of abandonment of agriculture, reforestation followed by urbanization has occurred in the PIE watershed as well (Schneider and Pontius 2001) (Fig 2.2). There have been substantial changes in the frequency of storms along the U.S. Atlantic coast, with the magnitude of change in storminess increasing at more northern latitudes (Hayden and Hayden 2003). At the PIE LTER changes in century-long storm frequency are pronounced and precipitation and evapotranspiration have increased significantly (Fig 2.3 Claessens et al., submitted). In the future, we can expect to see more frequent, larger storms and higher storm frequency variability as well. There have been decadal and century-long changes in sea level at PIE as well (Fig 2.4). Therefore, the PIE LTER study can be considered a microcosm for investigating the effects of these globally important changes and it should thus be possible to transfer lessons learned from the PIE LTER to other coastal regions.

There are numerous ways that these globally important issues are affecting the biosphere. In the PIE LTER we focus on how these issues influence organic matter and inorganic nutrient biogeochemistry and estuarine foodwebs. The inputs of organic matter and nutrients from land, ocean and marshes interact with the external drivers (climate, land use, river discharge, sea level) to dictate the extent and degree of nutrient and organic matter processing and determine the spatial patterns of estuarine productivity and trophic structure. Our overarching question is:

**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?**

Within the context of this overarching question, our program addresses two hypotheses about the effects of driver variability and long-term change on ecosystem dynamics and the effects of inorganic vs. organic matter inputs on estuarine foodweb structure.

**Hypothesis 1. The variability in land, ocean and atmospheric forcing is a major factor controlling the fate of allochthonous and autochthonous materials and the location and magnitude of primary and secondary production.**

All components of an estuarine ecosystem exhibit variation in space and time in response to external drivers (e.g., climate, river discharge and sea level) or in response to internal, biogeochemical and biological processes (e.g., nutrient cycling, population cycles and fish migrations). By comparing time-scale and intensity of processes, the relative importance of various physical or biological factors in controlling variation in process rates can be assessed and limits placed on the ability of one process to affect another (Hatcher et al. 1987). Processes that occur at similar scales are those likely to interact. Our research on the effect of changes in organic matter, nutrient and water fluxes on estuarine trophic structure and production requires that we evaluate variability in land and ocean drivers and assess the spatial and temporal scales over which the effects of these changes are likely to operate. Understanding the response of these systems to long-term changes in climate, sea level and land use first requires that we understand and can distinguish short-term variation from long-term trends.

**Hypothesis 2. The interaction of inorganic nutrients with the quantity and quality of organic carbon and organic nitrogen plays an important role in determining the trophic structure, production and efficiency of estuarine food webs.**

The delivery of organic matter and nutrients has a major effect on estuarine food webs. We know from metabolic studies that estuaries as a class are heterotrophic, consuming more organic matter than produced (Hopkinson and Smith in press) and thus dependent on allochthonous sources. This is not surprising as typically 1-2% of terrestrial NPP is exported to estuaries (Meybeck 1982). Most estuarine respiration is by bacteria (Hopkinson et al. 1989, Smith and Kemp 2003) due to the high C/N ratio and low lability of riverine organic matter (OM) (Hopkinson et al. 1998). Elevated inputs of inorganic N from watersheds have perhaps the greatest impact on estuarine condition (Bricker et al. 1999). N-enrichment (eutrophication) causes shifts in algal abundance, increases in algal productivity and standing stocks, and in extreme cases, hypoxia, anoxia and fish kills (Howarth et al. 2000a, b, Cloern 2001, Driscoll et al. 2003a, b). As watersheds become developed, organic matter export declines and inorganic nutrient export increases (Meybeck 1982, Raymond and Hopkinson 2003, Pellerin et al. submitted, Wollheim et al. submitted, Williams et al. submitted a,b,c). Major factors controlling the autotrophic-heterotrophic balance of estuaries include the balance between inputs of inorganic and organic nutrients (Kemp et al. 1997, Hopkinson and Smith, in press), water residence time and the lability of allochthonous organic matter (Hopkinson and Vallino 1995). With increased N enrichment, decreased organic matter inputs and perhaps decreased freshwater inputs to estuaries in the future, we can expect changes in foodweb structure, shifting from organic matter, microbially-based to inorganic nutrient, phytoplankton-based (Deegan et al. 1994).

**CHANGES IN OUR PERCEPTIONS OF THE CONTROLS OF FOODWEB STRUCTURE**

Early on we developed a trophic flow model and diagram (Fig 2.5) to synthesize our understanding of the effects of organic matter and nutrient inputs on trophic structure and function (Deegan et al. 1994). We envisioned 4 basic pathways of organic matter and nutrient processing that varied over decadal time scales in relation to long-term changes in the loading of organic matter and nutrients from watersheds:

**1) the classical grazing food chain:** inorganic nutrients - phytoplankton > 20  $\mu\text{m}$  - macrozooplankton - planktivores - piscivores, **2) the microbial loop:** organic matter - bacteria - microflagellates - microzooplankton - macrozooplankton - planktivores - piscivores, **3) a hybrid of the grazing food chain and the microbial loop:** inorganic nutrients - phytoplankton < 20  $\mu\text{m}$  - microflagellates - microzooplankton (the microbial loop) - macrozooplankton - planktivores - piscivores, and **4) a benthic food chain:** organic matter - to sediments - bacteria - benthic meio - and macrofauna - benthivores - piscivores.

This conceptualization, while perhaps a good representation of long-term equilibrium conditions, over emphasized the importance of organic matter and nutrient inputs from the watershed and does not reflect the dynamic variability of estuaries. Because riverine organic N inputs are greater than inorganic N inputs (Williams et al. submitted a, b), our flow analysis model suggested a hybrid grazing - microbial loop pathway dominating in the upper estuary with keen competition for nutrients between

phytoplankton and bacteria. We expected to find evidence of terrestrial organic C fueling higher trophic levels. We hypothesized that the benthic food chain would take on importance down estuary, where piscivore production would be supported from low quality organic matter inputs from the marsh. Our temporal focus was primarily decadal, the time scale over which we expected to see a shift toward the classical food chain as urbanization increased DIN loading relative to organic N.

Our perceptions of how estuarine ecosystems are structured and function have changed substantially over the past 6 years. We find that the effect of watershed OM or DIN inputs is greatly modulated by river freshwater discharge (Deegan and Garritt 1997, Holmes et al. 2000). We find that the most important input of organic matter is the marsh (Raymond and Hopkinson 2003) and that there are major recycling sources of DIN internal to the system that are controlled by salinity variations (Giblin et al. in prep). We have yet to observe the classical pelagic grazing food chain, rather phytoplankton blooms appear linked to higher trophic levels equally through both pelagic and benthic webs (Fig 2.6; Hughes et al. 2000). Benthic microalgal production is often an important base of the foodweb (Fig 2.6; Tobias et al. 2003a, b).

***Freshwater discharge is of paramount importance*** in controlling foodweb structure ***because of its influence on residence time*** of water throughout the estuary (Vallino and Hopkinson 1998). Interestingly, only Parker River flow is an important factor. Although Ipswich River flow is 10x the Parker, its input at the mouth of the estuary has no discernible effect on residence time or salinity within Plum Island Sound (Vallino and Hopkinson 1998). Residence time of water in the upper estuary decreases from 34 – 2 d as river flow increases from 0.01 to 10 m<sup>3</sup> s<sup>-1</sup> (Vallino and Hopkinson 1998). In the lower estuary tidal mixing has the greatest effect on residence time; seasonal increases in river flow only decrease residence time from 1.2 - 0.6 d. The relative importance of physical or biological factors depends on the time scales of physical and biological processes. The influence of organic matter and nutrient inputs on the estuarine food web is dictated by the time scales of important processes relative to water residence time. ***Thus, by controlling estuarine residence time, the interplay of freshwater discharge and tidal regime defines the template upon which ecological processes can operate.*** For example, algal blooms can only occur when water residence time is substantially longer than bloom doubling time. Hence algal blooms only occur during very low flow during summer (Holmes et al. 2000).

We also find that there are “spheres of influence” that vary over the length of the estuary and over seasonal or shorter time scales, where foodwebs develop in response to physical drivers plus DIN and OM inputs. We have modified the trophic flow diagram (Fig 2.5) to include benthic microalgae and a microalgal food chain, and to include a direct link between phytoplankton blooms and benthic macrofauna. Figure 2.7 illustrates the interplay between external drivers as they define a template upon which the effects of DIN and OM inputs on foodweb structure operate. The figure shows examples of 4 foodweb structures that develop under different hydrologic templates and loading conditions. The spheres of influence identify where these foodweb structures are likely to be found. In no sense do we mean to imply that foodwebs are static communities controlled exclusively from the bottom-up. Foodwebs are dynamic and feedbacks between organisms and environment are to be expected.

One result of our altered perceptions is that the role of watershed DIN and OM inputs must be assessed within the context of the hydrologic template. The vast majority of inputs occur during late winter / early spring, when biological activity is at its lowest. We need to determine the extent and the mechanisms by which any of these inputs are retained for use later in the year. Marshes are net sinks for C and N; what enables them to export as much C and N as it appears they do and still remain net sinks? We hope to resolve some of these uncertainties as our research program continues.

**PROPOSED RESEARCH QUESTIONS** – To address our overarching research question and hypotheses, we organize our research around 5 interrelated questions that define Programmatic

Areas. The scope of each question and the manner in which each fits in the overall program is illustrated with numbered boxes around portions of our conceptual diagram (Fig 2.5).

- Q1. What is the magnitude and long-term pattern of freshwater runoff and organic carbon and nitrogen and inorganic N loading from watersheds to the estuary?**
- Q2. How are tidal marsh processes and their connections to estuarine waters controlled by changes in land, atmospheric and oceanic forcing?**
- Q3. How do planktonic community structure and production respond to short and long-term changes in watershed runoff and the inputs of organic matter and nutrients?**
- Q4. 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?**
- Q5. How do the structure and function of higher trophic levels respond to changes in land, atmospheric and oceanic forcing as well as fisheries harvest?**

## **APPROACH**

We use a *combination of approaches* to address our research questions and hypotheses: 1) short- and long-term core measurements 2) short and long-term experiments, 3) comparative ecosystem studies and 4) modeling. The proposed research integrates estuarine biogeochemistry with studies of food webs and population biology of all trophic levels.

**Core measurements:** One of our goals is to detect and understand the effects of changes in physical, chemical, and biological features of the watershed, estuary and coastal ocean. As many of the human-induced pressures on estuaries such as climate change, sea level rise and land use change operate over time scales of decades or longer, this will require the *collection and management of data on core measurements* (Table 2.1). New “core” measurements that are proposed for the next funding cycle are described in the approach sections for the specific research questions. Detection and understanding of the effects of change will improve as our database becomes of sufficient duration to enable us to conduct retrospective analyses.

Our “core” measurements fit the 5 LTER core areas (Table 2.1) and address our overarching questions and specific research questions. 1) We measure temporal and spatial patterns of marsh and estuarine primary production and the effect of N+P enrichment on marsh, benthic microalgal and planktonic production. 2) We monitor temporal and spatial patterns of phytoplankton, marsh grass, bacteria, zooplankton, fish and shellfish numbers and community composition. 3) Inputs, stores and dynamics of organic matter are investigated in the watershed, marshes, and estuarine waters. 4) Watershed N dynamics, riverine N export and N cycling and movement through the estuary are tracked. 5) Finally, we address the issue of disturbance by examining changes in climate, sea level and land cover on trophic dynamics and biogeochemical cycles.

**Long-term field experiments** have been established to understand the importance of inorganic nutrients, organic matter sources, and the hydrologic template to estuarine function. We manipulate the relative amount and quality of organic matter in sites with different hydrologic template along the fresh to marine gradient of intertidal marshes using four kinds of manipulations: marsh surface nutrient enrichment (production of low quality OM), marsh detritus removal (removal of low quality OM), tidal creek nutrient and freshwater enrichment (stimulation of high quality OM production and alteration of hydrologic template) and tidal creek nutrient enrichment and foodweb manipulation (stimulation of high quality OM production and top-down effects) (Table 2.2; Fig. 2.30). By maintaining these experiments over long time periods, we will gain insight into how fluctuations in sea level, climate and river discharge alter the ecosystems response to our manipulations.

The tidal creek fertilization and foodweb manipulation experiment is our newest experiment and manipulations will be initiated this coming year. It specifically addresses questions about the effects of inorganic nutrient loading on coupled marsh-creek systems and examines the

interaction with species composition. Nutrients will be added to flooding waters to emulate chronic nutrient enrichment from land use change (Table 2.2). Because of complex feedbacks, a complete understanding of the long-term impacts of nutrient loading and changes in organic matter quantity and quality on coastal ecosystems will require the expertise of many; we will draw on the expertise of existing LTER investigators as well as new non-LTER scientists. During this experiment we will measure most of the processes described in the programmatic areas below (Q1-Q5). Models will be used to integrate experimental results and to predict the cumulative effects of nutrients and species changes on estuaries over decades.

**Comparative ecosystem research** enables us to test the generality of conclusions reached from site-specific research and to ensure that models are applicable across a wide range of coastal waters and ecosystems. We lead an LTER cross-site intercomparison of the controls of organic matter accumulation (critical to the maintenance of marsh elevation relative to sea level rise) and play a major role in the LINX intersite stream study. We will continue participating in 3 other intercomparisons (microbial biogeography, coupled hydrologic-biogeochemical watershed modeling, role of species interactions in ecosystem processes) initiated at the LTER Aquatic Scientists meeting organized by Hopkinson and Hobbie (Salt Lake City 2000 and continued at LTER ASMs in 2000 and 2003). Several of our short-term experiments and core observations are repeated at other sites by PIE scientists and other LTER and non-LTER scientists (e.g., marsh sediment elevation at the North Inlet, SC and Wells, ME NERRs, GCE and VCR). We have offered to coordinate those measures critical to addressing our research questions.

**Modeling** is our most effective means of integrating research across the various programmatic areas of the PIE LTER, of testing our understanding of ecosystem controls and linkages and of determining the new experiments most critical to furthering our understanding of estuarine trophic structure and productivity. Modeling is employed at two levels – 1) within each programmatic area and 2) linking programmatic areas (e.g., coupling a watershed model of land use change and river runoff with an estuarine model of community metabolism. See Synthesis section).

## PROPOSED RESEARCH

**QUESTION 1: What controls the magnitude and long-term pattern of freshwater runoff and organic C and N and inorganic N loading from watersheds to the estuary?** Box Q-1, Fig 2.5

**RATIONALE** - Our growing realization of the importance of hydrodynamic controls on the biogeochemistry and foodweb structure of Plum Island estuary gives renewed impetus to our long-term sampling and experimental plans for the upland watershed. Freshwater fluxes not only control the mixing and dispersion properties of the estuary but also provide an important, seasonally varying source of bioactive materials. The watersheds component of the PIE-LTER is well positioned to address several major issues in landscape and ecosystem ecology: (i) land-based activities and their spatial and temporal character are critical determinants of the capacity of the upland basin to retain organic matter and nutrients via the formation of biogeochemical hotspots (McClain et al. 2003); (ii) water and material fluxes exhibit nonlinear or threshold responses to environmental forcings (e.g. Aber et al. 2003, Gergel et al. 2002); and (iii) interactions between multiple environmental stresses, climate stochasticity, and management activities control ecosystem responses (Ollinger et al. 2002, Carpenter 2003, Dent et al. 2002).

We will build on four major classes of activities that characterize our existing LTER effort (monitoring, field experiments, GIS, and integrative modeling). We have learned much from our efforts to date. Runoff and inorganic nutrient exports are substantially greater from urbanized catchments (Williams et al. submitted a, Wollheim et al. submitted, Groffman et al. in press, Driscoll et al. 2003a, b) (Fig 2.11, 2.12). The density of wetlands in the basin is a key determinant of DON and DOC concentrations, an assertion found to hold regionally (Pellerin et

al. submitted; Raymond and Hopkinson 2003) (Fig 2.9). The bulk of N retention occurs in small headwater catchments (Wollheim et al. submitted; Williams et al. submitted a) (Fig 2.10), with declines in suburban catchments due to hydrological and biogeochemical changes associated with impervious surfaces (Wollheim et al. submitted, Burges et al. 1998) (Fig 2.12). We have found that the aquatic network itself holds “hotspots” and “hot moments” of nutrient retention and/or conversion from inorganic to organic forms (Williams et al. submitted a, Filoso et al. in press) (Fig 2.10, 2.33). GIS-based predictions of future land cover change show increased suburbanization (Fig 2.8) and concomitant nutrient loads (Schneider and Pontius 2001), with a substantial portion of anticipated loads to be ameliorated by land and aquatic ecosystem processes (Filoso et al. in press). Flowpath analysis based on field experiments (Pellerin et al. in preparation) indicates greater direct inputs of water to streams in suburban areas due to the presence of impervious surfaces (Fig 2.13), potentially compromising retention in riparian zones, groundwater, and soils. Reflecting basin-scale hydrologic dynamics, there is evidence for significant groundwater fluxes that cannot be quantified by headwater sampling, indicating the importance of surface/ subsurface links (Wollheim et al. submitted). These studies, taken together, further emphasize the importance of hydrological fluxes in delivering material to the coastal zone.

**Specific Research Questions:** *1a) How do spatial and temporal factors organize basin-scale outputs to the estuary?*

There are two scales of temporal forcing. Short-term exports of water and material from the watersheds are controlled primarily by climate variability such as floods, droughts, and spring freshets (e.g. Alexander et al. 1996). Longer-term exports are determined by progressive changes in land use, government regulation, atmospheric deposition, population, and water withdrawals (Driscoll et al. 2003a b, Aber et al. 1989, Aber et al. 2003, Caraco et al. 2003). Further, the internal spatial topology of source/sink locations modifies exports at the whole basin scale beyond those expected based on aggregate changes alone (e.g. Alexander et al. 2000, Seitzinger et al. 2002). Thus, we will test the notion that fluxes can be determined by first assessing the general level of constituent transport conditioned on long-term forcings, and then modified by temporal variations in runoff/discharge.

**Approach:** We will continue monitoring long-term hydrological and biogeochemical fluxes from our urban and forested headwater catchments, and from the two major basin mouths. A third, wetland-dominated headwater site will be added, given the importance of wetlands in controlling DON and DOC fluxes (Pellerin et al. submitted, Raymond and Hopkinson 2003). In addition to continuous discharge measurements, water samples will be assayed frequently for  $\text{NO}_3^-$ , TN and TP and monthly for pH, conductivity,  $\text{NO}_3^-$ ,  $\text{NH}_4^+$ ,  $\text{PO}_4^{3-}$ , DOC, DON, DOP, POC, PON, TP, and TSS. We will institute sampling of groundwater constituents during high and low water table periods in different land uses, using residential or public water supply wells.

Ongoing LINX-2 work in the basin will provide synoptic stream samples at low flow in 2004 and 2005 to characterize the spatial heterogeneity of loading and processing throughout the river network. Stable isotopes of water ( $^2\text{H}$  and  $^{18}\text{O}$ ) will be measured in these synoptic surveys, as well as in groundwater and precipitation samples, to address the age distribution of water.

**Modeling-** A model of source-sink topology (Constituent Transport Model) will be developed to explore how the distribution of sources and sinks controls export of materials from the watershed. This model will weight the source/sink strength of different ecosystem types and time periods based on GIS and extensive surface water nutrient data sets collected by PIE over the last 6 years (Table 1.2 Supplemental). Historical land use maps will be developed and land use change models applied (Pontius and Schneider 2001, Schneider and Pontius 2001) to construct historical and future source-sink topologies.

**Specific Research Questions:** 1b) *What are the key controls on water and biogeochemical sources, transformations, and sinks throughout the watershed?*

There is strong evidence that 70-90% of exogenous N loading is retained (Fig 2.10, 2.12 Williams et al. submitted, Wollheim et al. submitted, Howarth et al. 1996, Boyer et al. 2002). While it is clear that hydrological factors control retention over time and space, it remains unclear from the budgeting approaches taken in these studies whether the retention is terrestrial, groundwater, riparian, or riverine (Van Breeman et al. 2002). In addition, we do not know the short or long-term retention capacity of the ecosystem under continued high N loading. Further work is required and constitutes a major focus in our next phase of research.

**Approach:** We will continue to update our GIS data sets to track changes in land use, population, water withdrawals, and sewage treatment. We will develop forest-age and residential land use age maps to be used to better understand the considerable scatter observed in our land use vs. constituent relationships (e.g. Fig 2.11, Williams et al. submitted a, Pellerin et al. submitted, Raymond and Hopkinson 2003). The importance of headwater stream processing in overall watershed retention will be evaluated using experimental approaches of the LINX-2 study ongoing in the PIE watersheds in 2004 and 2005. Continued monitoring of the hydrology and constituents in headwater catchments and basin mouths (described above) will allow evaluation of retention strength of different land uses under different hydrologic conditions, elucidating mechanisms of retention. *Modeling:* Biogeochemical processing strength is strongly controlled by hydrological conditions. In addition to continued modeling with HSPF, we will refine a residence time based approach to predict variation in N retention in different ecosystem types, including the river network itself (Green et al. 2003, Seitzinger et al. 2002). A high resolution Water Balance Model that predicts isotopic composition of water based on mixing and fractionation will be applied to validate model estimates of residence time in various hydrologic components (soils, groundwater, river network) (Vorosmarty et al. 1998, Federer et al. 2003, Fekete et al. submitted).

**QUESTION 2: How are tidal marsh processes and their connections to estuarine waters controlled by changes in land, atmospheric and oceanic forcing?** Box Q-2 Fig 2.5

**RATIONALE** - Estuarine marshes act as transformers adjacent to tidal creeks and bays that intercept and modify material inputs from atmosphere, land and ocean (Weinstein and Kreeger 2000, Valiela et al. 1978). Variations in climate, riverine inputs and sea level affect not only internal processes such as primary production and accretion but also the strength of the marsh-tidal water linkage for sediments, nutrients and organic matter. Marshes also provide habitat critical to the development of higher trophic levels (Turner 1977, Deegan et al. 2000).

During the past 5 years we have gained an appreciation for large spatial gradients in marsh geomorphology and function, including non-uniform aerial extent of marshes and marsh tidal creek density along the estuarine axis, substantial porewater drainage from marsh edges during low tide, changing relative importance of N and P as factors limiting NPP changes along the length of the estuary, and apparently rapid marsh degradation in the lower estuary (Cavatorta et al. 2003). These spatial gradients are likely to influence the strength and nature of the linkage between marsh and adjacent tidal waters.

We have been assessing the variability of marsh primary production at PIE and examining if interannual changes in relative mean sea level have the same effect as at North Inlet (NI), SC (Morris et al. 1990, Morris 2000). Changes in relative mean sea level affect soil salinity, and productivity responds to changes in salinity (Morris 1995, 2000). We find that primary production at PIE is highly variable, appears to be related to changes in MSL (Fig. 2.14), and that productivity of PIE and NI marshes may be synchronous. The synchronicity of production has important implications for species that use the marsh. Like Valiela and Teal (1974), Sullivan

and Daiber (1974), Gallagher (1975), Patrick and DeLaune (1976), Mendelsohn (1979), Levine et al. 1998, Bertness et al. 2002 and others, we also find that PIE and NI salt marshes are N-limited (Fig 2.15), though NI marshes are secondarily P-limited while PIE is not. PIE freshmarsh is P-limited.

We find that sediment accretion increases in parallel with the increase in primary production and biomass density at NI brought about by fertilization (Fig. 2.16), consistent with Rogers et al. (1998), which demonstrates a feedback between primary production and sediment accretion, and presumably sea level and freshwater discharge by virtue of their effects on sediment salinity, nutrient loading, and primary production. Plant biomass at PIE and NI increased dramatically in fertilized plots, and in NI this corresponded to a rapid divergence in the elevations of fertilized and control plots, but not at PIE (Fig. 2.16). We believe a sediment deficit exists at PIE following the reforestation of the watershed, and that the present extent of marshes at PIE may be a legacy of deforestation following European settlement.

**Specific Research Question:** *2a) How are sediment accretion and primary production in tidal marshes altered by changes in freshwater discharge, material inputs and sea level?*

We have developed a model that predicts how marsh elevation and productivity adjust to changes in the rate of sea level rise (Morris et al. 2002). Our model predicts that the equilibrium elevation of the marsh is a function of the rate of sea level rise and sediment supply, and that there is an optimum rate of sea level rise for primary production. The model and supporting data suggest that marsh stability *requires* the equilibrium elevation of the marsh platform to be supraoptimal for primary production. Primary production responds positively to an increase in relative sea level (Morris 2000). At North Inlet, SC, increased productivity stimulates increased sedimentation and raises the elevation (Fig. 2.16). However, at sediment-poor Plum Island, increased productivity by fertilization has not resulted in greater sedimentation (Fig. 2.16). In both marshes, changes in elevation are episodic, probably a consequence of changes in belowground production and sediment supply via runoff. There also is evidence that PIE marshes, which are eroding rapidly around their margins and in interior ponds, are recycling eroded sediment onto the remaining healthy marsh. This recycling may account for the rapid rise in elevation seen at PIE during 2003 (Fig. 2.16).

**Approach:** *Primary Production* - We have long-term experiments in 3 major marsh types where plant census and porewater nutrient data are collected monthly. Plots receive monthly factorial N and P additions to determine nutrient controls on primary production and sediment accretion. Now that we have firmly established nutrient limitation (Fig. 2.15), we will census monthly the control plots only, but will continue the fertilization treatments. The SET measurements and end of season biomass measurements in fertilized plots will be used to track long-term trends in primary production. Complementary work on marsh productivity in South Carolina is being supported by NSF's LTREB program. The monthly census of plant heights is giving us unparalleled temporal resolution of salt marsh production that is not corrupted by spatial variability (Morris and Haskin 1990).

In 2003 we started long-term experiments with large-scale N and P additions in the a transition zone between *S. patens* and *Typha*. We plan to initiate another across the *S. patens* – *S. alterniflora* ecotone in 2004. These experiments will help to determine nutrient control of species distribution and sediment accretion, an experiment that was started by our graduate student Rob Daoust. The large-scale nature will facilitate participation by other scientists interested in the effects of fertilization in tidal marshes. We have also established a short-term experiment designed to determine the optimal elevation for *S. alterniflora* and the relationship between primary production and relative marsh elevation (Fig. 2.17). We plan to establish several of these experiments along the salinity gradient and with different species. Parallel experiments are being conducted in marshes in Louisiana and South Carolina. *Sediment Accretion* - We have

established SET (surface elevation table) platforms and feldspar marker horizons (Cahoon and Turner 1989, Boumans and Day 1993, Cahoon et al. 2002) at 12 sites across 3 major marsh types. Comparative fieldwork and model development, supported by a grant from USGS, is also carried out at North Inlet (Morris et al. 2002). Morris continues to be a leader of the LTER Network Intersite Comparison on Controls of organic matter accumulation in soils and sediments. *Modeling* - We will continue to develop our plant productivity – marsh elevation model, incorporating spatially explicit sediment accretion data and primary production measurements. This will be an active area of research, including work at the landscape scale where we expect to find that marsh accretion depends on geomorphological pattern, such as stream order. The generality of our findings is being tested by comparative research at North Inlet, SC.

**Specific Research Question:** *2b) How do indicators of organic matter and inorganic nutrient exchange between marshes and estuarine waters respond to variations in freshwater discharge and sea level?*

Concentrations of porewater nutrients in the marsh are typically an order of magnitude greater than in creek water and export of nutrients and DOM from the marshes to the tidal creeks appears to be an important process that affects the metabolism of the estuary (Howes and Goehringer 1994, Morris 2000, Raymond and Hopkinson 2003, Vallino and Hopkinson submitted), depending on hydrology and geomorphology. The water table in the marsh at PIE typically varies up to 1m during a typical cycle near the margins of the marsh (Fig. 2.18). On an estuary-wide basis this process delivers a significant load of nutrients and DOM to the creeks. We estimate that the total volume of water drained into creeks is about  $1,000,000 \text{ m}^3 \text{ day}^{-1}$ , which is  $\sim 10x$  the average Parker River discharge. As the hydrological forcing function, primary production, and pore water nutrients vary with MSL, there is likely to be an effect of sea level on the exchange of nutrients between the marshes and tidal creeks. The complementary effect of salinity variations on  $\text{NH}_4^+$  flux is investigated in Question 4.

**Approach:** A series of ground water level recorders in *S. alterniflora* and *Typha* marshes monitor the dynamic response of subsurface water in relation to tidal and climatic forcing. Characterization of marsh geomorphology and tidal creek drainage network configuration using remote sensing and GIS technologies is being augmented with an EPA grant to Morris/Torres/Hopkinson. *Modeling* - Complementary data is being collected on sediment structure, hydraulic conductivity, porosity and specific yield, which will be used to parameterize a model that will compute the quantity of water and nutrients leaving marsh sediments and entering tidal creeks on every tide. Marsh sediment ammonium exchange characteristics, and N losses due to denitrification are being collected under Question 4. Calculated N fluxes will be compared with patterns of estuarine metabolism conducted under Question 3.

**QUESTION 3: How does planktonic community structure and production respond to changes in organic matter, nutrients, and water fluxes?** Box Q-3 Fig 2.5

**RATIONALE** - The water column programmatic area concerns the linkages between land, marshes, ocean and estuaries through the input of dissolved and particulate organic matter (DOM and POM) and nutrients, and the effect of changes in climate, sea level and the watershed on these inputs. The conceptual model (Fig. 2.5) describes the hypothesized effect of major watershed changes on inputs that drive the composition and productivity of estuarine communities. The classical view is that high nutrient inputs favor large-celled phytoplankton. These are consumed by grazing zooplankton that are in turn consumed by fish. Our research has shown that this view must be modified to include strong links directly from phytoplankton to benthic invertebrates and fishes (Figure 2.6). And when nutrients inputs are high but residence times are low due to tidal dispersion and advection, benthic diatoms are the most productive microalgal community, directly feeding benthic consumers. If watershed inputs are high in

organic matter but nutrients are relatively low, bacteria may out-compete the algae for nutrients. The resulting microbial loop consumes the energy in the organic matter through grazing by microflagellates and microzooplankton. Little energy is available to the fish.

In the Parker River and Plum Island Sound, water residence times are so short (< 5 days ) during the late winter and spring seasons that populations of large-celled phytoplankton do not have time to develop within the estuary. Crump et al. (in press) estimated residence times of 3-5 days in the spring and 8 days in the summer and fall (Fig 2.19). However, during late winter and spring large phytoplankton cells are carried by the tides into the Sound when a nutrient-rich plume moves down the coast carrying an algal bloom. During the June to September period of low river discharge large-celled phytoplankton blooms occur regularly in the upper Parker River when residence time is >7 days.

We need to improve our knowledge of the ecology of algae in the estuary but have been held back until now by our lack of taxonomic expertise. This can now be solved and we will create a baseline on distribution and biomass of algal species in the estuary. The next step is to determine how important various size classes and types of algae are in primary productivity.

In the conceptual model (Fig. 2.5), organic matter inputs to the water column influence the growth of bacteria and, in this way, may lower the importance of the grazer food chain. We have learned that there are two main sources of DOC to the Parker River. One source, runoff from land, changes its <sup>14</sup>C age during incubation; there is a portion resistant to decomposition that is more than a thousand years old and a young portion that disappears during a long incubation (Fig 2.20). The other source, which is the dominant one, is the large input of DOC entering the estuary from the tidal marshes. This input is revealed by <sup>13</sup>C-DOC samples along the estuary that deviate from a standard dilution curve (Fig 2.20) and implicate *Spartina* as the major DOC source.

DOC is partially consumed by bacteria and the remainder is exported to the ocean. During the LTER project we have gained new quantitative information on the fate of organic matter in the estuary. Measurements of the dawn to dusk changes in oxygen and carbon dioxide concentrations along the long axis of the Parker River–Plum Island Sound estuary show that the estuary is clearly heterotrophic (Fig 2.21). That is, more organic matter is consumed in the tidal waters and benthos than is produced. This extra organic matter likely comes from the fresh and salt marshes and from algal blooms in the oligohaline part of the estuary (Crump et al. in press). Bottle incubations reveal that bacteria are responsible; filtration to remove large cells but not bacteria before incubation removes only a few percent of the respiration. The calculation of respiration from the change in CO<sub>2</sub> in the free water depends on the gas transfer velocity. This velocity is usually calculated from equations utilizing the wind speed to estimate turbulence. During the project we have learned that turbulence generated by the tide in shallow estuaries is much more important than wind in controlling the gas transfer velocity (Zappa et al. 2003).

Our knowledge of the types of planktonic bacteria involved has changed dramatically during the LTER. Crump (et al. in press) characterized the bacterial community during summer and fall and discovered a novel estuarine community that only occurs when residence times are long enough and bacterial growth rates are high.

**Specific Research Question:** *3a) What algae and protozoan species are present in the plankton and what is the size distribution of algal productivity?*

The LTER now has available some much-needed expertise in the taxonomy of planktonic algae and protozoans. We will create a photographic, web-based catalog that will allow us to 1) develop a baseline list of algal and protozoan species present in the plankton against which to measure species change over the next decades, 2) document the size distribution of algal productivity, and 3) begin to study the control of bacterial abundance by microflagellate grazing.

**Approach:** Dr. Patrick Patterson, now at the MBL, will make a special study of the Plum Island Estuary and compile photos and a list of at least 100 of the common planktonic organisms. We will combine the identification with the quantification method (numbers and biomass) of settling chambers and inverted microscope. During the project we will survey the annual and spatial variation of the organisms and their biomasses. The data on protozoans will be the first step to estimating the grazing of flagellates on bacteria. In addition, we will add a size filtration step to our  $^{14}\text{C}$  primary productivity measures after incubation and analyze parallel, non-radioactive samples for algal species.

**Specific Research Question:** *3b) What are the interactions between bacteria, their species and metabolism, and different chemical conditions in the estuary?*

Our previous work has documented phylogenetic shifts in space and time in community composition of bacteria within the estuary. To study effects of different salinities on bacteria, we will incubate freshwater, estuarine, and marine plankton samples containing bacterial communities in dialysis bags transplanted along the estuarine salinity gradient. We will examine changes in communities as well as in individual bacterial populations to estimate the growth rates of various types of bacterioplankton. A related question concerns the response of bacteria in the estuary to different types and quantities of DOM and nutrients. We ask two basic questions: are bacteria a source or a sink for nutrients and do bacteria react differently to DOM from the marsh and from the river?

**Approach:** The salinity experiment will use dialysis bags (Gasol et al. 2002, Simek et al. 2002) suspended in the estuary and containing a sample minus the large algal cells and zooplankton. We will monitor bacterial production, respiration, and average growth efficiency with standard techniques, track community composition changes with DGGE separation of PCR-amplified rDNA plus DNA sequencing (Crump et al. 2003, Crump et al. in press), and quantify known populations with quantitative Real Time PCR using primers designed for our population mapping study (Suzuki et al. 2000, Suzuki et al. 2001). We also plan to explore the relationship between phylogenetic composition and ecological function by following shifts in the active bacterial community, staining cells with the nucleic acid stain SYTO-13 and isolating cells containing high quantities of DNA and RNA using the sorting capacities of a flow cytometer (delGiorgio et al. 1996, Gasol & Del Giorgio 2000). The resulting fractions (high- and low-DNA and RNA) will be analyzed and compared using DGGE and DNA sequencing.

The DOM and nutrient interaction experiment will be carried out in the dark in closed bottles. Bacteria communities will be filtered onto membrane filters, resuspended, and added to 0.2  $\mu\text{m}$ -filtered samples of river water or marsh runoff (or seepage) water with different concentrations of added nutrients. We will monitor the response of bacterial numbers (fluorescence microscopy) and biomass (as carbon trapped on GFC glass fiber filters). In incubations of samples without added nutrients we will investigate whether or not the bacteria immobilize or mineralize nutrients, such as ammonium, from the DOM (sink or source).

**Specific Research Question:** *3c) What is the metabolic response of the planktonic system to natural variations in nutrients and organic matter?*

Changes in inputs to the estuary as well as in within-estuary processes lead to variation of organic matter and nutrients from season to season, year-to-year, and site-to-site. These variations lead to changes in algal and bacterial productivity; analyses of the changes produce many insights about the response of the planktonic community. We will continue to make use of the rapid survey technique in which  $\text{O}_2$  and  $\text{CO}_2$  concentrations along the entire estuary are sampled at dusk and dawn (Fig 2.21). A major problem is interpreting the data because both benthic and planktonic organisms cause the changes in dissolved gases. We will use planktonic and benthic respiration measurements to estimate the strength of these processes independently.

**Approach:** The production and respiration measurements will continue seasonally over the estuary. In addition, research will be continued on the controls of gas transfer in estuaries. This research will focus on the role of tides vs. winds in creating turbulence in surface waters.

In a separate experiment, we will measure the planktonic respiration in whole-sample, flask incubations. Benthic respiration will be measured as a part of Question 4. *Models* of primary production and respiration (e.g., Vallino et al. submitted) will be used for the analyses. We will improve the analysis with better coefficients for the transfer of CO<sub>2</sub> across the air-sea interface.

**QUESTION 4: 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?** Box Q-4 Fig 2.6

**RATIONALE** - The benthos is an important site of organic matter mineralization in estuaries, consuming substantial amounts of O<sub>2</sub> and releasing nutrients to the overlying water (Nixon 1981, Boynton and Kemp 1985, Hopkinson and Smith in press). Benthic processes are especially sensitive to changes in both freshwater runoff and organic matter inputs. First, the benthos is the primary site of nutrient removal due to denitrification, with up to 75% of watershed N inputs being denitrified (Seitzinger 1988). Freshwater discharge, by changing sediment salinity, affects estuarine denitrification because, in general, freshwater sediments are more efficient at removing nitrogen through coupled nitrification / denitrification (Seitzinger et al. 1991, Rysgaard, et al. 1999). In the oligotrophic portion of the PIE estuary, coupled nitrification / denitrification decreases dramatically during summer and dissimilatory nitrate reduction to NH<sub>4</sub><sup>+</sup> (DNRA) exceeds direct denitrification, greatly reducing sediment gaseous N<sub>2</sub> losses (Fig 2.22). Our site is not unique as DNRA also becomes a major benthic N process at some times of the year in other estuaries (An and Gardner 2002). The adsorption of nutrients onto sediment particles is also strongly dependent upon salinity (Gardner et al. 1991, de Jonge and Villerius 1995). In zones where the salinity varies, NH<sub>4</sub><sup>+</sup> can effectively be stored in the sediments during low salinity conditions and released as the estuary becomes more saline (Fig 2.23). Although this process does not alter total NH<sub>4</sub><sup>+</sup> release on an annual basis, the effect can be great because it occurs when river discharge and watershed N loading are lowest; salinity-enhanced NH<sub>4</sub><sup>+</sup> flux contributes significantly to summertime algal blooms (Holmes et al. 2000) (Fig 2.24). We also find evidence that microbial community structure changes with salinity (Mondrup 1999, 2000) and that salinity optima for nitrification changes as the community changes over time (Fig 2.25). In conjunction with the PIE Microbial Observatory, we find that there are two very distinct groups of nitrifiers, a relatively stable community in saline waters, dominated by a few specialists, and a more variable and diverse group in the upper estuary, likely reflecting the greater seasonal variation in salinity. Another factor controlling benthic N dynamics are benthic microalgae (BMA) (Tobias et al. 2003). The distribution of BMA is closely related to the temporally varying hydrologic template.

The benthos plays an important role in organic matter decomposition and in controlling estuarine trophic structure. Because of the much longer residence time of particles in sediment than in the water column and oscillating redox conditions (Aller 1994), the benthos plays a key role in the processing of low quality organic matter, such as terrestrial and marsh detritus. Some organisms are capable of obtaining a portion of their C and N directly from detritus (Cammen 1980) making the benthic foodweb shorter and more efficient (Newell 1982, Findley and Tenore 1982). In addition, in spite of a relatively small contribution to the overall carbon stocks, there is a growing recognition of the importance of the contributions of benthic algae in estuarine food webs.

**Specific Research Question:** 4a) *How do variations in the salinity distributions in the estuary determine the magnitude and timing of nutrient release to the water column?*

Sediment salinity changes are not confined to oligohaline subtidal sediments. Indeed, the intertidal region experiences greater salinity changes (due to ET), has much higher  $\text{NH}_4^+$  absorption coefficients (Koop-Jakobsen and Giblin 2002, Koop-Jakobsen 2003), and is 10x larger in area than the subtidal region. Our hypothesis is that although marshes may function as a net sink for N due to denitrification and burial, during the summer, after marsh macrophyte N demands are satisfied, marshes may act as a major N source by releasing adsorbed  $\text{NH}_4^+$ .

**Approach:** *Long-term measurements* – We will continue our “core” measures of benthic fluxes twice a year at upper and mid-estuarine sites but also expand into intertidal vegetated sediments in the same region. *Process studies:* In intertidal sediments, we will make the same measures of sediment adsorption capacity at varying salinity and the same intensive process measurements (denitrification DNRA, nitrification, N mineralization) that we did in subtidal sediments. This work will be the focus of a newly accepted Ph.D. student from Denmark, who made preliminary measurements as part of his M.S. work (Koop-Jakobsen 2003). We will also carry out similar experiments on the time lags in the response of microbial communities and processes to changes in salinity. *Modeling* – We will continue development and refinement of a model of benthic N cycling, including the effect of salinity change.

**Specific Research Question:** *4b) How do benthic nutrient fluxes and metabolism in different regions of the estuary respond to variations in the quality and quantity of organic matter inputs?*

There are strong spatial and temporal gradients in the sources and quality of organic matter inputs to the estuary along its length (Raymond and Hopkinson 2003). We measure how total benthic respiration and inorganic nutrient and DOM fluxes change along this gradient. Both the quality of the organic matter and the environment in which it is decomposed (electron acceptor availability) are important factors affecting the dynamics of nutrients and organic matter in sediments. Over the past 6 years we have also become aware of the potential importance of benthic autochthonous production by microalgae. BMA distribution and importance vary greatly at PIE (Tobias et al. 2003a, b) and probably from year to year in response to variations in turbidity and salinity (which may indirectly control populations of macrofaunal grazers) brought about by variations in sea level and river discharge.

**Approach:** *Long-term measurements* – We will continue “core” benthic flux measures twice a year at the upper and mid-estuarine sites. Over the long term we will learn how fluxes respond to natural variations in river discharge and sea level change. We also use our core respiration measurements to partition the proportion of the total metabolism (Q-3) to the benthos. *Process studies* – Labeled ( $^{14}\text{C}$ ) organic matter from either terrestrial POM, marsh detritus, or planktonic detritus will be added to sediments from two salinity zones. Comparison of both a high and low salinity site will enable us to compare fluxes where either sulfate reduction or methanogenesis is the dominant mode of anoxic metabolism. The label will also be followed through the benthic food web. To begin to assess the importance of benthic algal production, we will include light cores along with dark cores in our measurements of benthic metabolism. As a special study, we also plan to make similar measurements to those done by Tobias et al. (2003a) to assess the effect of benthic algae in processing nitrogen and influencing N fluxes and denitrification.

**Specific Research Question:** *4c) What is the relative importance to higher trophic levels of C and N from organic matter of different qualities and how does this vary with hydrology?*

C and N flow may become more uncoupled in benthic food webs as the quality of organic matter decreases. Field surveys of organism C and S stable isotopic signatures indicated preferential utilization of marsh-derived organic matter by benthic organisms. Use of terrestrial detritus was equivocal (Deegan and Garritt 1997). However, in a whole system  $^{15}\text{N}$  addition, it was apparent that some organisms that were thought to be tightly linked to marsh detritus for C can exploit phytoplankton for a major portion of their N requirements (Hughes et al. 2000). We are

compiling information from long-term “core” measures on year-to-year variability in food sources and comparative measures of growth on different types of detritus.

**Approach:** *Long-term measurements* – We collect samples of the bivalves *Mya* and *Geukensia* annually and use the variation in the  $^{13}\text{C}$ ,  $^{15}\text{N}$  and  $^{34}\text{S}$  to assess differences in the importance of phytoplankton vs marsh detritus to benthic filter feeders (Fig 2.26). This gives us another indirect measure of how year-to-year variability in hydrology affects the relative contribution of marsh detritus and phytoplankton to benthic food webs (see Q2). *Process studies* – We will take advantage of a whole system  $^{15}\text{N}$  addition experiment to be conducted as part of the tidal creeks research program (see synthesis section) to determine the relative importance of various organic matter sources in fueling different benthic populations (Hughes et al. 2000).

**QUESTION 5: How do the structure and function of higher trophic levels respond to changes in land, atmospheric and oceanic forcing as well as fisheries harvest?** Box Q-5 Fig 2.5

**RATIONALE** - The highly productive estuary ecosystem provides critical nursery and feeding habitats for a variety of fish, shellfish, and other biota. Food web support is clearly important to higher trophic level production (Kneib 1997, Deegan et al. 2000). In addition, distribution, production, and habitat choice are influenced by the physical environment at both the microhabitat (Eggleston et al. 1999, Phelan et al. 2001) and landscape scale (Hughes et al. 2000, Levin and Hay 2003). Initially, we focused on the importance of organic matter sources and simple physical controls (e.g., salinity) on higher trophic levels. We demonstrated that food webs vary spatially in response to the local availability of organic matter (marsh and algal), with little influence of watershed inputs (Deegan and Garritt 1997, Hughes et al. 2000). We also learned that river flow (Hughes et al 2000) and the hydrodynamic template (Tobias et al. 2003a, b) are more important controls on food webs than originally assumed.

Our new research will focus on the feedback between the biota and ecosystem organization and function and the role of the hydrologic template in influencing that feedback. For example, it is now recognized that predation by top consumers (fish such as striped bass or mummichog) on intermediate trophic levels (green crab, *Crangon* or benthic worms) may alter the algal and microbial communities and can affect ecosystem biogeochemical cycling and productivity (top down control: Polis et al. 2000, Posey et al. 1999, Silliman and Zeiman 2001). Our work with striped bass and mummichog has led us to believe that these top down controls on intermediate trophic levels maybe very important in Plum Island (Ferry 2003, Haas et al. In prep.) The response of estuaries to nutrients depends on the biota of the system (Micheli 1999, Cloern 2001, Conley et al. 2000, Hughes et al. 2000, Deegan et al. 2002). If these feedbacks are important then species alterations through overfishing, extinction and exotic introductions may strongly affect estuarine ecosystem function (Enserink 1999, Jackson et al. 2001).

**Specific Research Question:** 5a) *How does the production of higher trophic levels vary over the long-term with changes in organic matter, nutrients, water flux, habitat availability and predators?*

Understanding how the spheres of influence (river, marsh, marine) differ in their support of biota and change with sea level or discharge is key to predicting the long-term sustainability of higher trophic levels. Our current field experiments indicate that brackish marshes support higher growth rates and survivorship than salt marshes (Haas et al. in prep.). Isotopic measurements of key functional groups (Fig 2.26) suggest that river-influenced areas have higher interannual variability in trophic support compared to marine-influenced areas. Ultimately, linking changes in the spatial extent of suitable habitat with changes in food webs will enable us to predict the effects of sea-level rise and alteration of river discharge on secondary production.

**Approach:** We will continue our “core” measurements of the abundance of small forage fishes (complete survey every 2-3 years) and the annual isotopic survey of 10 key functional groups

(Fig 2.26) at 3 sites distributed from fresh to marine sites. We will add to our long-term measurements estimates of annual growth of key species (*Fundulus*, *Menidia*, *Mya*, *Crangon*) based on length-frequency analysis. *Modeling* – The long-term changes in population size and isotopic composition will be coupled with spatially explicit habitat suitability and hydrodynamic models to develop relationships among changes in water flux (fresh and salt), sources of primary production, and production of higher trophic levels over decades.

**Specific Research Question:** 5b) *How do higher trophic levels regulate trophic structure and the flow of energy and nutrients?*

Trophic cascades were previously thought to be common only in aquatic systems with discrete homogeneous habitats, vulnerable prey, and simple grazing food webs but cascades have now been documented in a wide range of systems (Pace et al. 1999, Polis et al. 2000). High resource quality, simple communities, and rapidly cycling nutrients can enhance trophic cascades (Mather 1998, Polis 1999, Chase 2000) while omnivory and disturbance can have either a positive or negative effect (Polis et al. 2000). Even where they occur, trophic cascades are not likely to be equally strong thus clarification is needed on role of top predators in open bay systems and in ecosystems where omnivory plays a role in complex food webs.

**Approach:** First, to understand how trophic cascades might operate in a detritus-based ecosystem dominated by an omnivorous fish, we will remove mummichog from two salt marsh creeks as part of the LTER long-term tidal creek fertilization experiment. Top down control will be determined by comparing ‘fish removal’ creeks to reference and nutrient enriched creeks. Second, in open bay habitats, striped bass are a dominant predator and exhibit flexible and aggressive foraging on fish and invertebrate prey (Ferry 2003, Ferry and Mather in prep. Fig 2.25). We will continue long-term monitoring of both predator (MA Div. of Marine Fisheries data) and prey populations and take advantage of the current increase in striped bass abundance to examine impacts of this predator (Fig 2.25). Additionally we will begin process-oriented measurements on the physical and biotic cues striped bass use to select prey and habitats. We will measure movement of striped bass, relative to physical conditions (temperature, current, salinity, depth, substrate) and prey (available and consumed) with acoustic tags and mobile and fixed receivers in the Rowley River estuary. *Modeling-* An integrated food web model (developed as part of TIDE) will be used to evaluate the top down role of mummichogs in salt marshes. We will evaluate striped bass movements and feeding using a dynamic behavior model that examines the consequences of individual behavior patterns to predict growth consequences of movement. Long-term data on forage fish and predator abundance (Q5a) will be analyzed for the influence of top predator abundance (effect of fishing pressure) on prey populations.

**Specific Research Question:** 5c) *How does the spatial configuration of habitats influence the production and function of higher trophic levels?*

The spatial configuration of habitat interacts with the location within the estuary to determine habitat suitability and ultimately fish production (Kneib 1997, Deegan et al. 2000, Webb and Kneib 2002). Despite the universal acceptance of marshes as important nursery habitats, there is a surprising level of uncertainty about how key attributes of a marsh vary spatially along the estuarine gradient and thus influence fish production. In addition, preliminary results from a spatially explicit, individually-based simulation model indicate that in all salt marsh configurations, rising sea level will increase predation but have little effect on growth (Fig 2.28). Understanding the controls of growth and survivorship is key to predicting how changes in land, atmospheric and oceanic forcing at the landscape level will affect higher trophic levels.

**Approach:** We plan a series of experiments to determine the controls on fish production in marsh habitats across the estuarine landscape. First, comparison of fish production and food webs in the tide creek fertilization experiments will provide information on the importance of

detritus or algae for trophic support. Second, we will conduct growth and predator exclusion experiments, establish marsh-flooding requirements and determine the food webs (gut content and stable isotopes) in different marsh types. *Modeling* - We will continue to refine our spatially-explicit model of mummichog growth, mortality and migration to include a better representation of the heterogeneous nature of the environment (Demers et al. 2000, Whipple et al. 2000, Bian 2003) and scale the model to the landscape level by linking it to the appropriate LTER hydrodynamic model (extent, duration and depth of flooding) and the marsh geomorphology model (Q2) to predict how fish production varies across a changing marsh landscape.

#### **SYNTHESIS** Box Q-6 Fig 2.5

We use three main approaches to synthesize the knowledge gained from the individual programmatic areas (Q1-5) to address our overarching question and test our hypotheses: long-term experiments, whole-system  $^{15}\text{N}$  additions, and modeling.

**Long-term experiments:** Our long term experiments, described under “Approach”, are not only an important means of testing specific research questions but also integrate our research program and rigorously test our models. In these experiments we have manipulated inorganic nutrient inputs, and both the quality and/or quantity of organic matter available to higher trophic levels (see Table 2.2 and Fig. 2.30). In the experimental plots we measure the same processes being measured across the estuary in each of the specific research areas, (including nutrients, primary production, plant and algal species, fish and invertebrate species composition and abundance, marsh surface elevation and peat decomposition), however, all the measurements are focused in the same place. In several of these experiments, we will use whole-system  $^{15}\text{N}$  additions to measure changes in N cycling and modeling to integrate across variable spatial and temporal scales. We then can use the data from experimental plots to calibrate models to the wider range of conditions in our experiments.

**Whole-system  $^{15}\text{N}$  additions:** Whole-system  $^{15}\text{N}$  additions have been a very effective means of understanding the feedbacks and interactions among foodweb structure and biogeochemical processing. For example,  $^{15}\text{N}\text{-NO}_3^-$  additions to the upper Parker and Rowley River regions of the estuary showed the critical importance of the hydrologic template. In otherwise similar environments, the Parker with long water residence time developed a plankton bloom and had both pelagic and benthic links to higher trophic levels, whereas the Rowley with short residence time developed a foodweb based on benthic microalgae (Fig 2.29). The addition of stable isotopes also provides another way of robustly testing our models under either ambient or experimental conditions. For example, we have built biogeochemical-foodweb models that successfully mimic observation of N pools in the estuary. However, the lack of agreement in the modeled and actual tracer data suggests that some of the flows must be wrong (see below). Because of the power of this approach,  $^{15}\text{N}$  additions will be used to compare across treatments in the long-term experiments described above to understand the importance of changing ecosystem drivers on food webs and biogeochemical cycles.

**MODELING** (Box Q-6 Fig 2.5): Modeling is an essential component of our program used to integrate both within and across programmatic areas. In each **programmatic area, models** are used to enhance and test understanding of specific experiments or mechanisms governing the process under study (See prior Q1-Q5 sections). For example, work has begun on individual based models (IBM's) that examine the influence of habitat and food availability on higher trophic level dynamics (Q5) and on long-term marsh accretion and loss (Q2). These focused models, or the understanding derived from them, are incorporated into **whole system models** which are broadly divided into 1) watershed modeling and 2) estuarine modeling. The watershed modeling consists of hydrology and biogeochemistry models that deliver water, nutrients and organic matter to the estuarine model. The estuarine modeling consists of hydrodynamic transport models that include flooding and drying of the marsh platform and several

biogeochemistry-food web models operating in the water column, benthos and marsh. We are also using modeling to explore new theoretical ideas. In particular, we are developing a model that describes ecosystem biogeochemistry from a metabolic perspective governed by a thermodynamically based goal function. In all modeling, data assimilation techniques are used to facilitate model calibration and prediction as well as to update real-time models.

**Watershed Modeling** – In collaboration with USGS, we implemented the Hydrological Simulation Program-Fortran (HSPF) to spatially simulate hydrology and biogeochemistry in the Ipswich watershed (Filoso et al. in press, Zarriello and Ries 2000, Kirkby et al. 2000) (Fig 2.31). The model accurately predicts Ipswich River discharge over both the calibration and validation domains (Fig 2.32). Ambient nutrient concentrations ( $\text{NH}_4^+$ ,  $\text{NO}_3^-$ ,  $\text{PO}_4^{3-}$ ; monthly in main stem and seasonally in tributary streams) were used to calibrate upland and stream biogeochemistry sub-models. Predicted concentrations of  $\text{NH}_4^+$  and  $\text{NO}_3^-$  along the Ipswich River compare reasonably with observations (Fig 2.31) allowing us to identify “hot spot” areas of DIN removal in the watershed.

To examine impacts of land use change on watershed nutrient export, we use our land-use prediction model (Q1) to project land use 100 years into the future and use HSPF to forecast  $\text{NO}_3^-$ . The land-use model projects 44% of the current forest will be urbanized resulting in a 38% increase in  $\text{NO}_3^-$  loading to the estuary (Fig 2.33). Simulations run under a pre-European settlement scenario clearly indicate the impact of human settlements and land use change on  $\text{NO}_3^-$  delivery to the coastal zone (Fig 2.33).

Because of HSPF’s wide spread use and its comprehensive biogeochemistry submodel, we will continue to use it as our main watershed hydrology-biogeochemistry model. However, we have found HSPF difficult to use as a focused research tool because its comprehensive nature means that hundreds of parameters require calibration, and often parameter values are not unique (Doherty and Johnston 2003). Consequently, we are also developing focused watershed models that will improve our understanding of the processes responsible for DIN release and uptake (see Q1). These new models should be scalable to other watersheds with minimal data as they do not require extensive parameterization.

**Estuarine Modeling – Hydrodynamic and Constitutive transport Models:** We have developed, and are actively developing, several estuarine hydrodynamic models applicable to different spatial and time scales. A 1D, tidally averaged, advection dispersion model has been used to study residence time characteristics of the Parker River and Plum Island Sound (Vallino and Hopkinson 1998), to understand controls on the autotrophic-heterotrophic nature of the estuary (Hopkinson and Vallino 1995), and to estimate gross primary production, community respiration and net ecosystem production (Vallino and Hopkinson submitted) (Fig 2.34). To better predict water movement at smaller space and time scales, a 1D, branched, tidally explicit model using USGS Full Equations Model (FEQ) has been developed for the Rowley River and Sound, and is being extended to the full estuary. With this model we are able to flood and dry marsh platforms, obtain velocities and water elevations in multiple tidal creeks (pseudo 2D), but still retain fast execution time (Fig 2.35). For constitutive transport needed for biogeochemistry-food web modeling, we plan to couple our FEQ model with the EPA WASP model. To obtain spatial representation on the marsh platforms and in the Sound, we have developed a 2D, vertically averaged, finite element (FE) model that employs a kinematic approximation (gravity wave balanced by friction only) to the shallow water equations. The model is coupled to a groundwater model to alleviate numerical singularities associated with drying the marsh platform (Ip et al. 1998) (Fig 2.36 and see PIE website). The 2D hydrodynamic model drives an associated 2D, FE, constitutive transport model.

We employ the different hydrodynamic-constitutive transport models depending on the needs of our studies. While the 2D, FE allows for high spatial resolution, it requires significant data input,

and computational times are orders of magnitude greater than the 1D models. Since we require fast execution times for developing biogeochemistry and food web models, we use the 1D models for development, and embed the finalized biogeochemistry model into the 2D FE model for production runs that require spatial resolution. We have also begun porting our 2D model to run on parallel computing architectures, such as the 64 AMD nodes Beowulf cluster at the Ecosystems Center. We are using VECFEM (Schonauer and Adolph 2001) for this work.

**Biogeochemistry-Food Web Models:** To help us understand and synthesize field or experimental observations in the context of our overarching goal, we have developed both simple and complex biogeochemistry-food web models (Fig 2.37) that can be embedded into our transport models. These models have been developed to track  $^{15}\text{N}$  so that data collected from tracer experiments can be used to test our understanding (Fig 2.38). We get good agreement between model and standard biomass or N concentration observations, but obtain poor results for  $^{15}\text{N}$  tracer data, which indicates that we do not fully understand all the connections and feedbacks among components. We use the tracer data to improve our understanding of trophic interconnections. Developing the open water pelagic and benthic models were the focus of the first LTER funding. Over the next funding period we will emphasize development of the marsh ecosystem-biogeochemistry model in conjunction with the new long-term experiments.

Our biogeochemical-food web models target mostly planktonic organisms where the continuum hypothesis holds. For higher trophic levels that display patchy distributions and behavior, such as fish, the continuum hypothesis breaks down. To understand how higher trophic levels interact with habitat and prey availability, we have begun development of individual based models (IBM's) (Sullivan et al. 2003) for mummichog and striped bass (Q5). We plan to use output from our hydrodynamic and biogeochemistry models to provide a virtual habitat for fish to roam within as dictated by behavioral and bioenergetic algorithms. By comparing model output to observations, we will be able to improve our understanding on what governs fish distributions and productivity for the studied species.

The models described above are applicable to relatively short timescales (hours to decades); however, part of our core research involves understanding how marine and terrestrial drivers alter marsh geomorphology over long timescales (decades to centuries). We have begun experiments to test theories that describe marsh stability based on sea-level rise, nutrient levels and sediment inputs (Q2 and long-term experiments; Morris et al. 2002). The marsh elevation model will be incorporated into a spatial landscape model for PIE (Fig 2.39). Our objective is to examine how marsh topography and drainage will change as a function of sea level rise and sediment delivery. The marsh topography model will be run in an iterative mode with the 2D hydrodynamic model. Given the marsh topography, the 2D hydrodynamic model will be run to determine sediment-loading patterns. With the sediment loading patterns, the marsh elevation model will be run for long duration (5-10 years), which will result in altered marsh topography. This iteration procedure will allow us to run the model over many decades with only periodic runs of the hydrodynamic model that is computationally intensive.

**Data Assimilation** – All our models contain large numbers of parameters whose values are poorly known. We use a combination of laboratory, mesocosm, and field observations to determine model parameter values via data assimilation techniques (Vallino 2000). When we are unable to obtain good model fits to data, this indicates model structural errors are present and that we are not accurately capturing the true nature of the processes underlying the observations (Giblin and Vallino 2003). This information is used to design experiments to elucidate the process uncertainties.

To extract the greatest information from observations, we employ linear (Wan and Vallino submitted) and nonlinear (Vallino and Hopkinson submitted) inverse techniques, which typically provide information of process rates or flows between compartments not directly measured.

These techniques have the advantage of having few or no parameters, but have limited predictive capability as a consequence.

We also use data assimilation techniques to take advantage of our real-time water quality and climatological data (see <http://www.pielter.org>). We can run a version of our estuarine biogeochemistry model in forecast mode and use extended Kalman filtering (Carmillet et al. 2001, Allen et al. 2002), or similar data assimilation techniques, to update model predictions with the real-time observations. Once demonstrated, these techniques will be extendable to other coastal systems where models and real-time data are available, and would be particularly useful in coastal environments that experience periodic hypoxic or anoxic conditions.

**Theoretical Modeling** – We are employing models to test and advance theories that may lead to a better understanding of the fundamental principals that govern biogeochemistry and ecological systems. In particular we are examining the use of thermodynamic goal functions to describe ecosystem biogeochemistry (Vallino et al. 1996, Vallino 2003) (Fig 2.40). In this approach, the entire ecosystem is represented by a set of metabolic half reactions, but instead of modeling organisms or guilds, emphasis is placed on allocation of protein to metabolic reactions. Reaction rates are determined by solving an optimization problem that maximizes a thermodynamic goal, such as exergy (Bendoricchio and Jorgensen 1997, Jorgensen 1994), subject to thermodynamic, kinetic, stoichiometric, resource and cellular allocation constraints. This modeling approach is adept at handling ecosystem structure changes due to altered ecosystem drivers.

#### **RESPONSE TO REVIEWERS COMMENTS FROM 3-YR REVIEW:**

We here address each of the four issues raised by the external review committee during our 3-yr review and included in the cover letter from NSF program directors Gholz and Taylor. **1) “The lack of sufficient and adequate lab facilities, investigator and student housing, and education and outreach space compromises future opportunities and growth of the program”:** MBL has since purchased for LTER use the Marshview Farm in Newbury, MA, which consists of double house presently capable of sleeping 13 and a large 2+story barn. MBL retrofitted house wiring, etc, and converted a walkout basement to lab space. We have obtained NSF planning grant funds to plan the future use and design of the barn. We expect that within a year, we will be seeking additional funds to retrofit the barn to accommodate our future housing, laboratory, outreach and meeting needs. We continue to lease the Rowley house, which provides additional housing and lab space for 8 and provides ready access to field sites and boats. Also see Site Management. **2) “the small scale spatial treatments of nutrient addition at the SET sites may generate criticism”:** These experiments have conclusively indicated which macronutrient is limiting in saline and oligohaline intertidal marshes. They are similar in size to plots at other sites and they allow us to compare the responses of marsh plots to fertilization across a large latitudinal gradient. We acknowledge the limitations of extrapolating from such small plots so we are adding 2 large-scale N and P manipulations in saline (2004; across *S. alterniflora* to *S. patens* ecotone) and oligohaline (2003; the *S. patens* to *T. angustifolia* ecotone) regions. Each experimental treatment is 5 x 25 m. (Q2, Table 2.2) **3) in regard to molecular water column studies, “interactions can be difficult to tease apart, and expanded efforts in this arena should be weighed in the context of priorities in other areas”:** the molecular characterization of bacterial community structure was largely supported by the Plum Island Microbial Observatory. Question 3 (water column planktonic system) focuses on the planktonic foodweb including the microbial loop and aquatic biogeochemistry. While molecular approaches are providing critical new information on microbial systems, they are but one of many approaches that we will use over the next 6 years. Refer back to Research Q3. **4) “the degree to which internal processes such as N-fixation, denitrification, and long-term burial are important to quantify, relative to (whole system) stable isotope approaches to defining the overall system N cycle must be clear in the renewal proposal”:** We will continue and expand process-level studies of the N cycle in

both the subtidal and intertidal sediments. Whole system  $^{15}\text{N}$  additions are extremely useful for understanding the interaction between N cycling and foodwebs, information not easily gained in small-scale the process-level studies. However, we do not rely on these whole system experiments by themselves for understanding the N cycle over larger scales. Instead, we combine these experiments with detailed process studies to elucidate details of the N cycle in specific regions of the estuary (e.g. Tobias et al. 2003a). While our long-term goal is to close the N budget, we will concentrate on those aspects of the N cycle most effected by changes in water, nutrient and organic matter inputs.

## **SIGNIFICANCE OF PROPOSED RESEARCH**

Humans are altering the ecosystems of the world at rates not previously experienced. Understanding and predicting how multiple stresses affect the sustainability of ecosystems is one of the most crucial challenges in environmental biology. Today we have the situation where local stresses, such as nitrogen loading or species changes, affect ecosystems at the same time that global stresses, such as sea level and global temperature rise, impact the same systems. Predictions of the future state of most ecosystems are weak, because we do not have information on ecosystem controls across a broad suite of ecosystems, as well as information on how units of the larger landscape interact. Understanding the relative importance of different controls (e.g., biotic versus physical) on ecosystem processes across a broad array of ecosystem types will allow us to make decisions based on general principles and not have to evaluate every site or ecosystem as a special case.

The research outlined in this proposal will contribute to a better understanding of how ecosystems in general respond to changes in major drivers, while providing specific information on coastal ecosystems. Understanding the response of a variety of ecosystems to global changes in nutrient cycles (Vitousek et al. 1997, our central question and long-term experiments), the determinants of transformation “hot spots” in ecosystems (Q1 watershed, Q2 marsh), the importance of biotic controls relative to physical controls (Q3, Q4, Q5) and understanding how disturbance is propagated across landscapes (Synthesis and modeling) is needed to predict the future state of ecosystems. Because the proposed nutrient and species composition manipulations are similar to those that have been conducted in other ecosystems, we will be able to compare the results in detritus-based aquatic ecosystems to similar experiments done in lakes, streams, forests and grasslands. We are well on our way to being able to couple spatially explicit land use change models, with coupled hydrologic-biogeochemical watershed models, and with coupled 1D and 2D hydrodynamic-biogeochemical – foodweb models. It will take longer to couple watershed models to landscape models of marsh deterioration or development. Our linked models will provide a modeling framework and approach that can be extended to other land-water coupled ecosystems.

We have outlined an ambitious research program for the next 6 years. Success of the program will require continued leveraging of LTER funds, which we have been very successful at over the past 6 years (see Budget Justification materials). By the end of the next 6 years we envision ourselves in a position of truly predicting some of the effects of land use change, climate change and sea level rise on estuarine ecosystems.

At the end of the next funding cycle, we should be poised to begin an LTER synthesis book on the PIE LTER. We would also like to be in a position to extend our results to the entire New England region, in collaboration with Hubbard Brook and Harvard Forest LTERs. Finally, we expect to make progress towards even greater inclusion of the social sciences in the PIE LTER and the addition of Gil Pontius as a PI should help us develop this area.

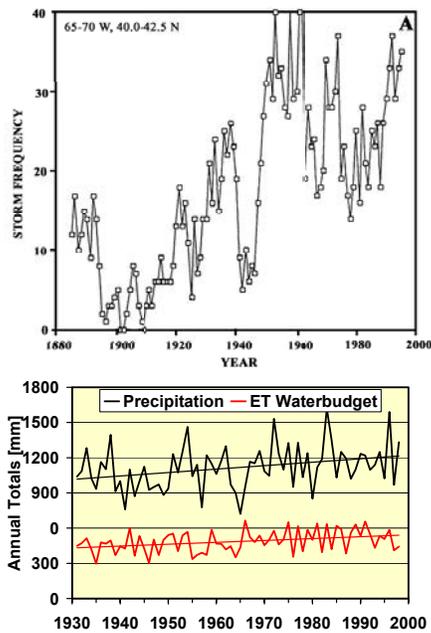
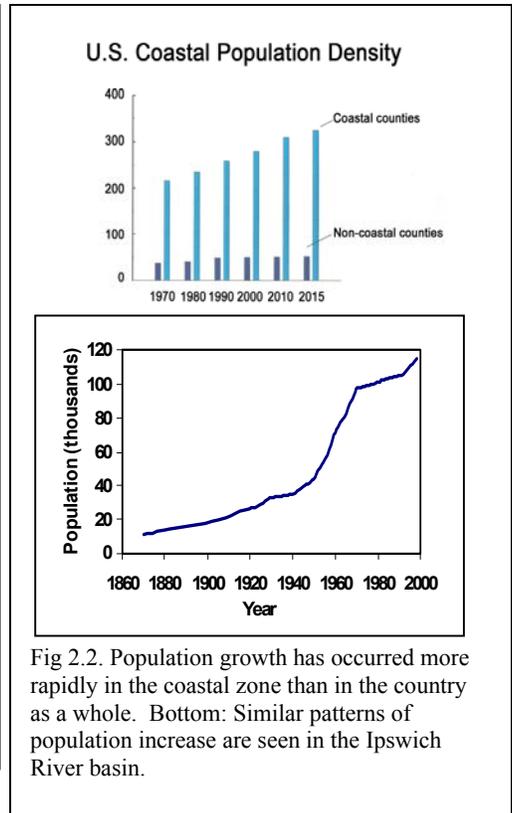
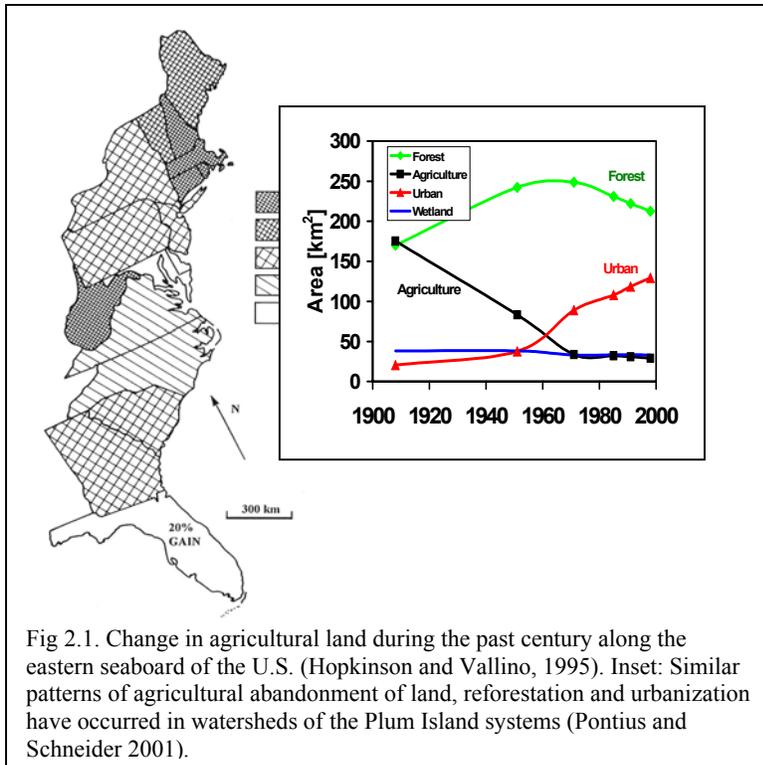


Fig 2.3. Storminess has increased with increasing latitude in the past century, with it tripling at PIE (Hayden and Hayden 2003). We have evidence that both precipitation and evapotranspiration have increased over the past 70 years in the Ipswich River watershed (Claessens et al. submitted). The relatively greater increase in ET has resulted in a net decrease in the river runoff coefficient. Changes to the hydrologic cycle are occurring worldwide (Peterson et al. 2003).

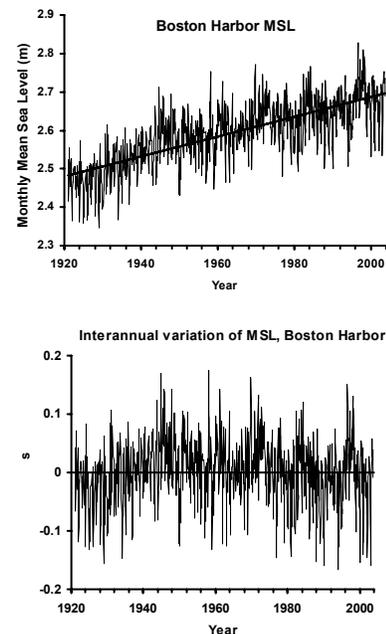


Fig 2.4. Sea level rise is a global issue. Over the past 80 years at PIE, it has been increasing at a rate of  $2.65 \text{ mm yr}^{-1}$  as recorded at the Boston NOAA station. Superimposed on the long-term trend is substantial monthly and annual variability. Short-term changes in mean sea level on the order of 20-30 cm can mean the difference between whether the marsh floods or not.

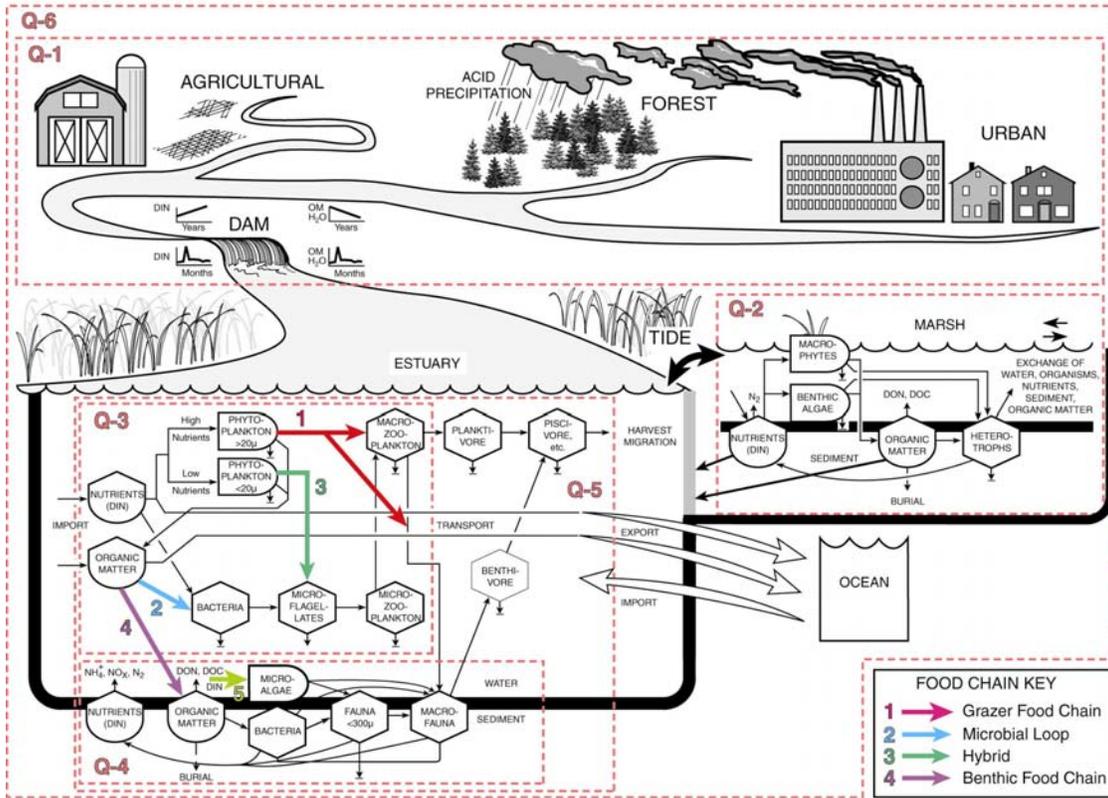


Fig 2.5. Conceptual model illustrating the collective integration (Q-6) of the biological and physical transformations of organic matter and inorganic nitrogen derived from watersheds (Q-1) and marshes (Q-2) and processed by organisms of the marsh (Q-2), estuarine water column (Q-3, Q-5) and benthos (Q-4). “Q”s and associated boxes refer to programmatic area covered by each of the Research Questions.

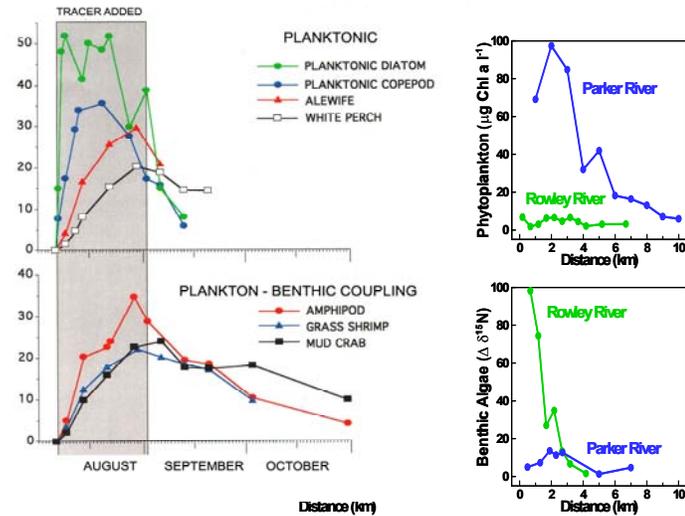


Fig 2.6. Evidence from a whole system  $^{15}\text{N}$  addition experiment for both planktonic and benthic foodweb links between bloom-forming phytoplankton and higher trophic levels. Graph shows the isotopic enrichment of water column and benthic organisms in the upper Parker River during and after isotope addition. The planktonic copepod and benthic amphipod became equally enriched relative to the bloom-forming diatom. Enrichment patterns show that two fish, alewife and juvenile white perch, feed in the water column on planktonic copepods and that larger white perch become increasingly benthivorous (Hughes et al. 2000). Graphs to the right illustrate the importance of water residence time: when water residence time is long, phytoplankton are the principal primary producers (top right), while when residence time is short benthic algae are the principal autotrophs (Tobias et al. 2003).

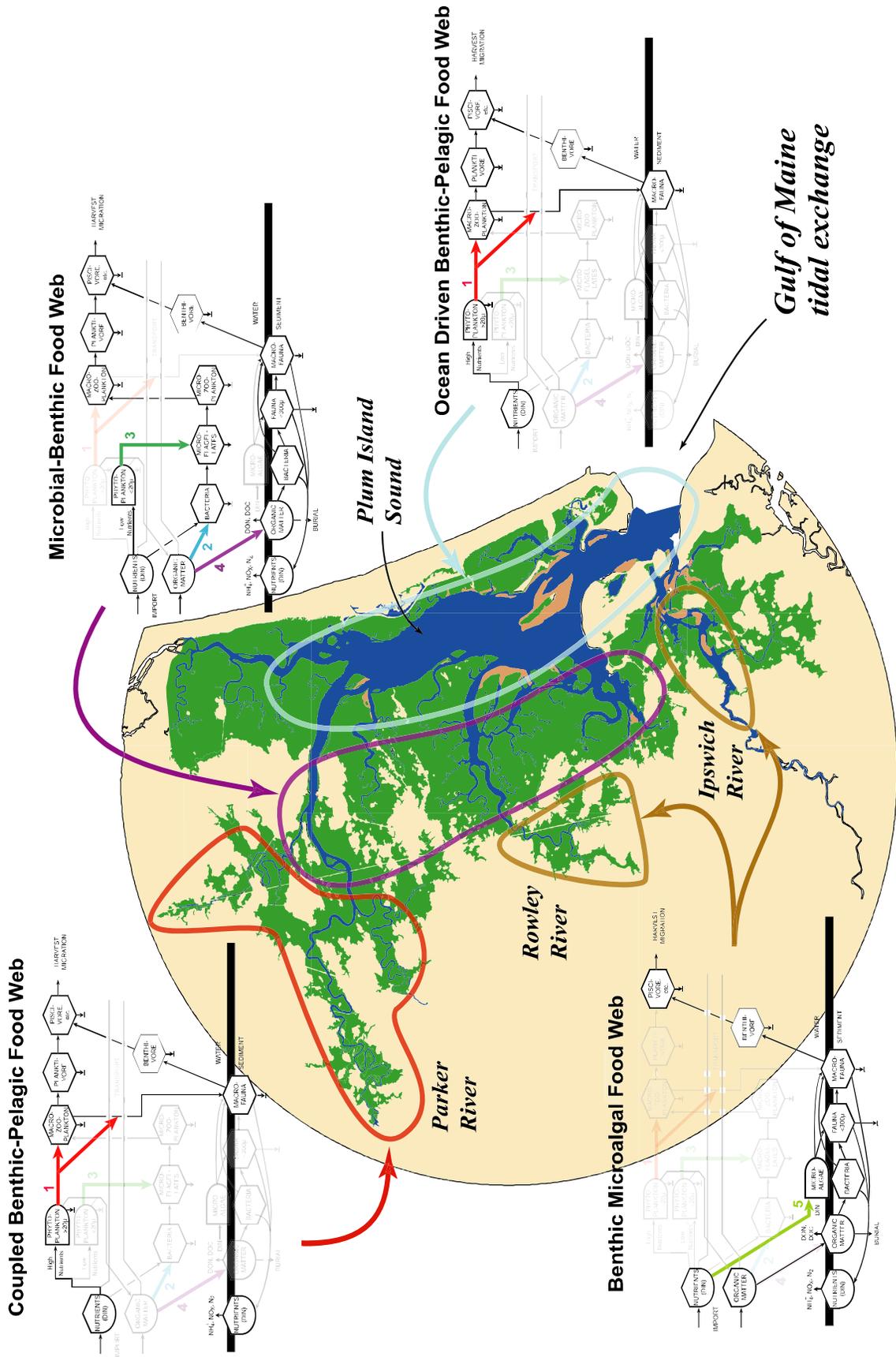


Fig. 2.7 External drivers, especially H<sub>2</sub>O residence time, define a template whereupon the effects of DIN and OM inputs on foodweb structure operate. Here we show 4 foodweb structures that develop in areas of the estuary that have different hydrodynamic templates and loading combinations.

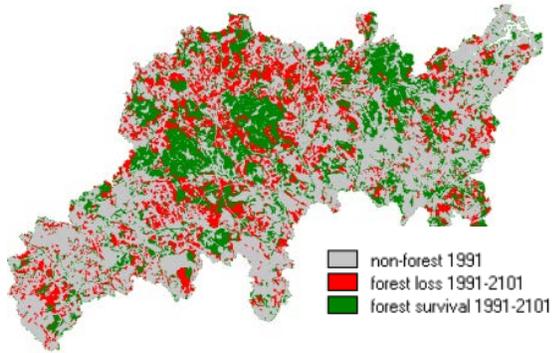


Fig 2.8. Land use change models have been developed using historical land use data to predict deforestation in the Ipswich watershed over the next century (Schneider and Pontius 2001). Predicted changes have been linked with biogeochemical models to model future changes in water and nutrient exports. We will develop maps of forest and residential age to understand contemporary variability in nutrient export.

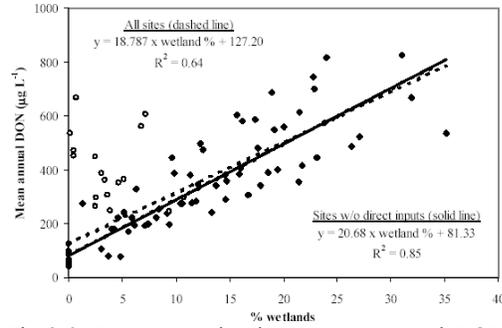


Fig 2.9. Percent wetlands vs mean annual DON conc. in streams and rivers of the northeastern U.S. region (with ~40 streams in the PIE watershed; Pellerin et al. in review). Wetland ecosystems are abundant in the PIE watersheds, and strongly control hydrology and biogeochemistry. We will institute long-term monitoring of a wetland-dominated catchment to determine how wetlands influence variability in water and nutrient exports to the estuary.

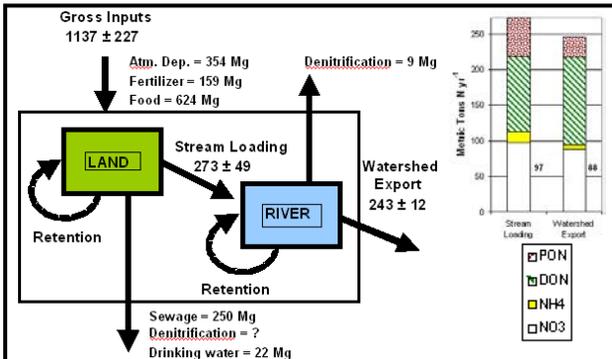


Fig 2.10. Nitrogen budget (metric tons/yr) for the Ipswich R. watershed during a wet period (Williams et al. submitted). Most N loading is stored or denitrified prior to reaching the aquatic network, which itself acts to transform N (right panel). Planned watershed efforts will focus on understanding year-to-year variability and the persistence of N retention.

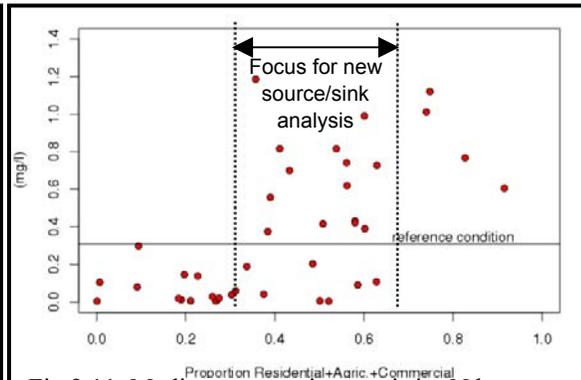


Fig 2.11. Median stream nitrate+nitrite-N between April and October 2001 vs land use in headwater catchments. The greatest range in concentrations occurs when the percent developed landuse is between 30 and 70%, a range over which we will concentrate sampling and modeling efforts to better elucidate controls on N flux.

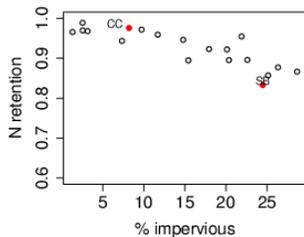


Fig 2.12. N retention (storage and/or denitrification) during 2001-2002 vs % impervious surface in headwater catchments. N export increases faster than N loading with imperviousness (Wollheim et al. submitted). Continued long term monitoring will allow us to determine year-to-year variability in retention and begin to understand the mechanisms whereby this high N retention occurs.

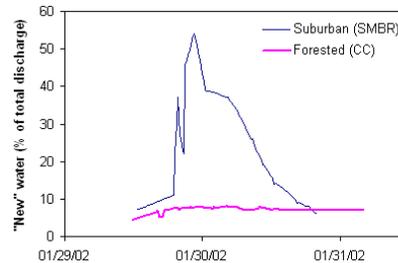


Fig 2.13. Fraction of total discharge that is composed of “new” water following a rain event in streams draining suburban and forested catchments, using silica and deuterium isotopes as tracers. New water is much more important in the suburban catchment, bypassing biogeochemically active subsystems.

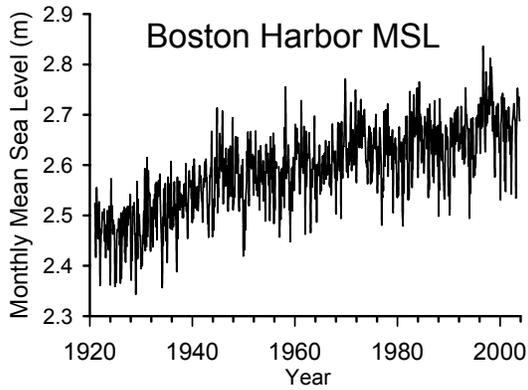


Fig 2.14 Monthly mean sea level (m) in Boston Harbor. MSL varies seasonally by about 20 cm due to changes in density (thermal effects). This seasonal cycle is highly variable owing to changes in climate and can have a large effect on the flooding frequency of salt marshes, which are situated at an elevation high in the intertidal zone.

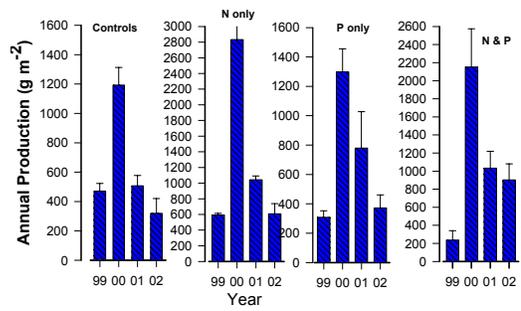


Fig 2.15. Annual aboveground production of *S. alterniflora* at PIE in control, N, P, and N+P fertilized plots. Note the difference in scale of the ordinates. The response to P did not differ from the controls; the response to N+P did not differ from the response to N alone.

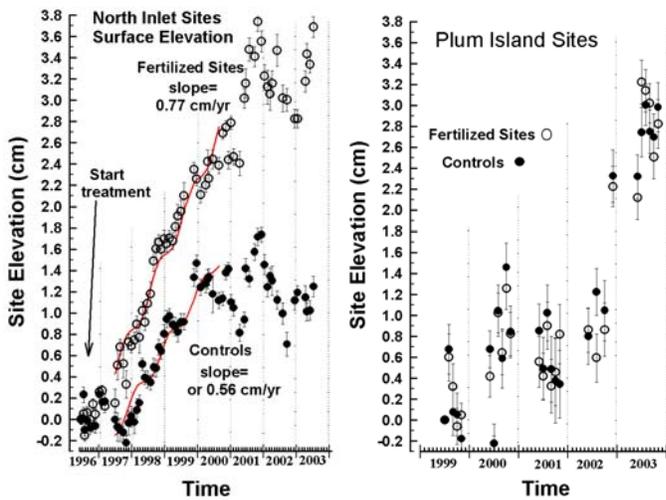


Fig 2.16. Relative elevations of the marsh surface at NI South Carolina and PIE. Note that higher plant density (by fertilization) has raised the level of accretion in sediment-rich NI marshes, but higher plant density in PIE marshes has failed to increase accretion rate.



Fig. 2.17. A bioassay experiment shown here at PIE is defining the responses of *S. alterniflora* to relative elevation. This experiment will be replicated along the salinity gradient and will be expanded to include *S. patens*.

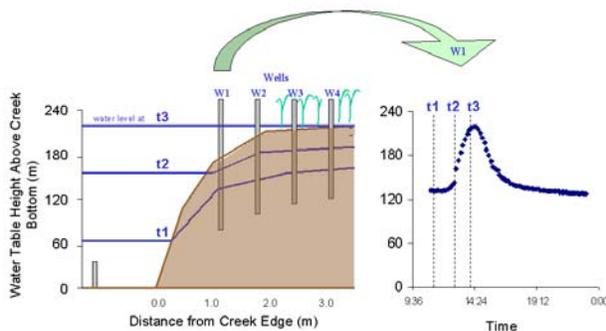


Fig. 2.18. Changes in the water table height as a function of distance from the marsh edge and tide stage at PIE.  $t =$  time when specific water levels are plotted. Graph at right is for Well-1, closest to creek edge

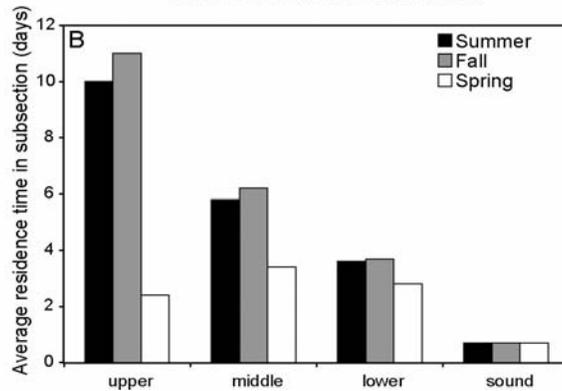


Fig 2.19. Average residence time of water in each subsection on summer, fall, and spring sampling dates (from Crump et al. (in press)).

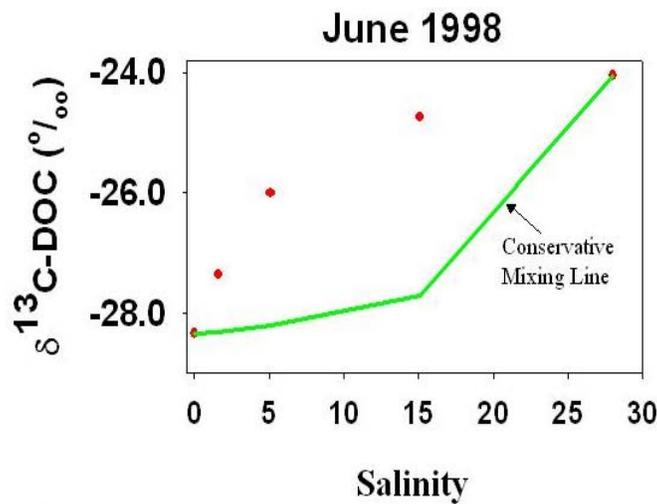


Fig. 2.20. Delta  $^{13}\text{C-DOC}$  in the Parker River, June 1998 shown by circles. Also shown is the conservative mixing line that indicates the values if only mixing of the freshwater and seawater occurred. Methods are given in Raymond and Hopkinson (2003).

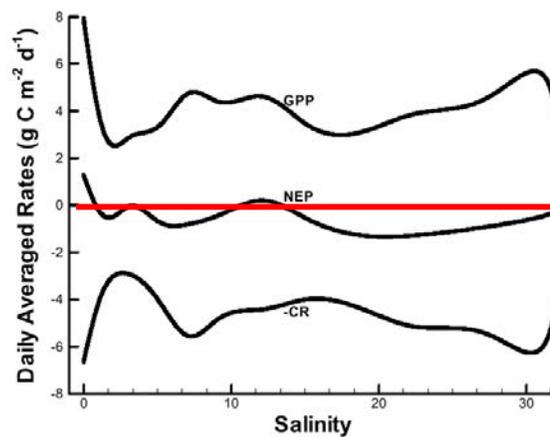


Fig 2.21. Depth integrated gross primary production (GPP), community respiration (-CR, plotted as negative value) and net ecosystem production (NEP) integrated over a 24 hr period as a function of salinity along estuarine axis. From Vallino and Hopkinson (submitted). NEP is positive in the oligohaline part of the estuary because of the diatom bloom, negative (heterotrophic) in most of the estuary, and approaches zero at the seaward end of the transect.

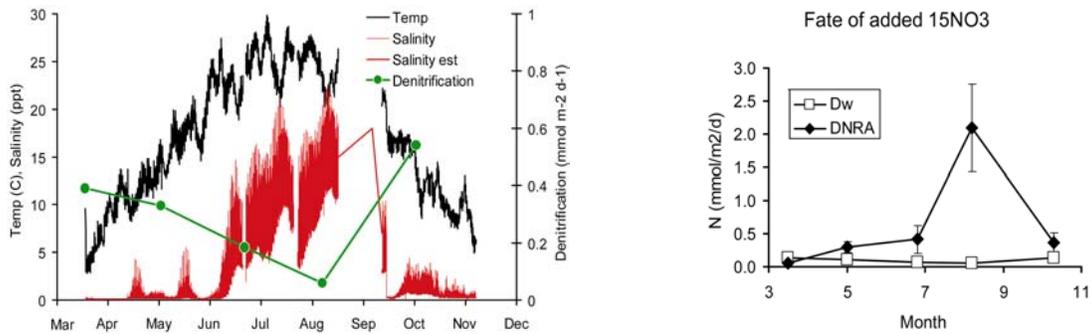


Fig 2.22. a) Temperature, salinity and rates of coupled nitrification and denitrification over the season in the Upper Parker River Estuary. Salinity increases over the summer as runoff decreases but also shows changes corresponding to spring neap and daily changes in tide height. Coupled nitrification/denitrification shows an inverse trend with temperature and reaches minimal rates during late summer when salinity is highest. b) The fate of added <sup>15</sup>N nitrate added to the sediments from the same site as above. In spring direct denitrification (Dw) exceeds dissimilatory nitrate reduction to ammonium (DNRA). DNRA peaks in late summer, as Dw and coupled nitrification/denitrification (Fig 4-1a above) reaches minimal values.

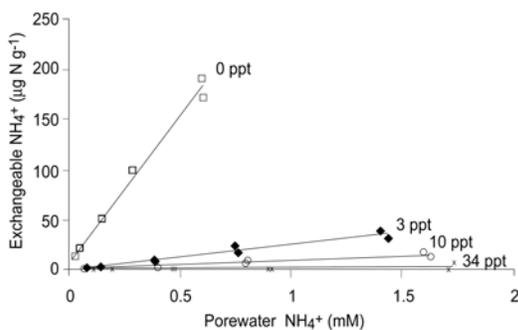


Fig 2.23. Changes in the ratio of adsorbed (exchangeable) NH<sub>4</sub><sup>+</sup> and dissolved NH<sub>4</sub><sup>+</sup> in the porewater with salinity in sediments from the upper Parker River Estuary. At 0 PSU, approximately 68% of the NH<sub>4</sub><sup>+</sup> in sediments is adsorbed onto particles while less than 32% is dissolved and free to diffuse into overlying waters. At high salinity nearly all of the NH<sub>4</sub><sup>+</sup> is free. This leads to a large efflux of NH<sub>4</sub><sup>+</sup> from sediments in mid-summer (Weston in prep, Hopkinson et al. 1999).

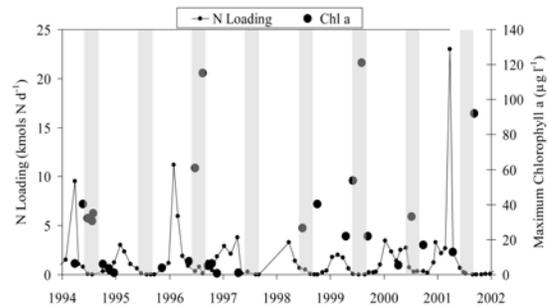
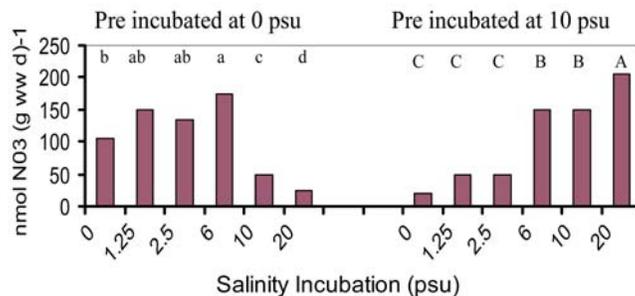


Fig 2.24. Relationship between N inputs from the watershed and Chl a concentrations in the Upper Parker River Estuary. The majority of the N inputs enter during the spring freshet while the major phytoplankton bloom occurs during summer (stippled line) when external inputs are low but water residence time is long. Our data suggests that internal recycling, driven in part by salinity changes, supports the mid-summer blooms.



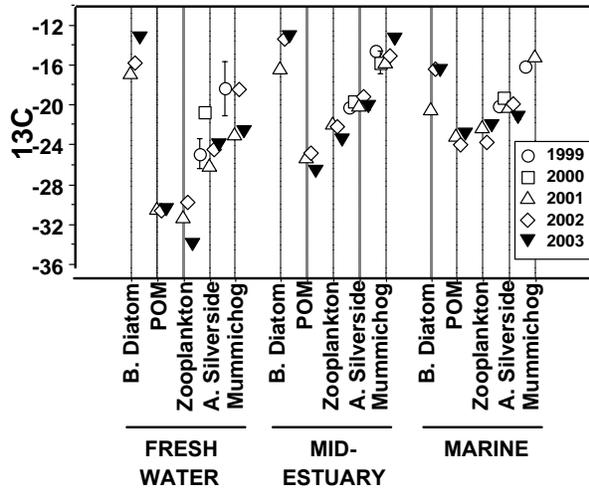
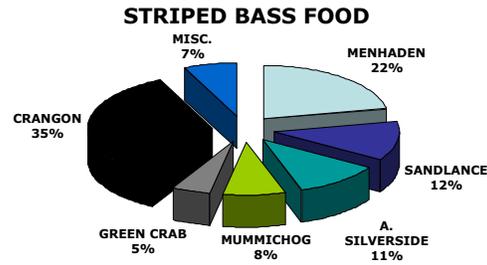


Fig 2.26. The different zones of influence are reflected in the overall more enriched  $\delta^{13}\text{C}$  values in the marine site compared to the riverine site. Isotopic variation within and among key functional groups is more variable in riverine influenced sites compared to marine influenced sites. Only 5 of the 10 functional groups sampled are plotted.

A



B)

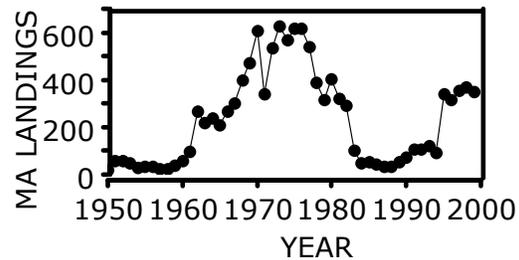


Fig 2.27. In the Rowley River (1999) about 60% of striped bass diet is based on species that use salt marshes such as mummichog, A. silverside and *Crangon* (Ferry 2003). Striped bass population size in MA is increasing suggesting that their predatory impact is increasing (Div. Marine Fisheries data).

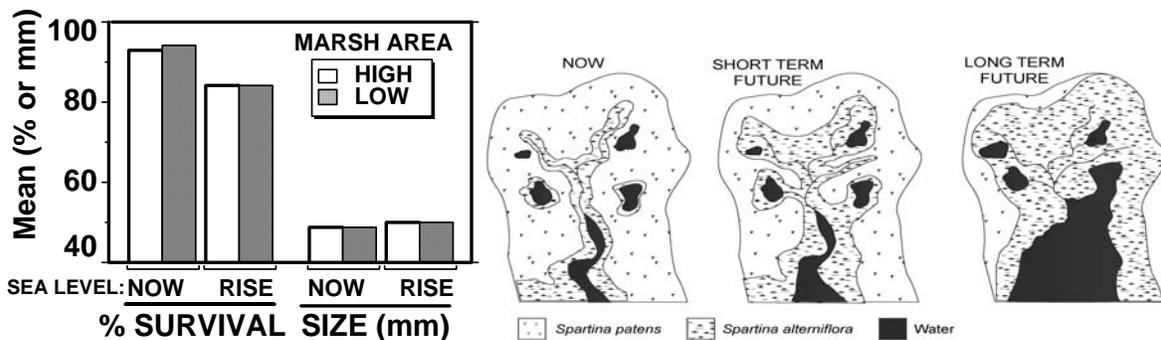


Fig 2.28. Preliminary results from a spatially explicit, individually-based simulation model indicate that in all marsh configurations rising sea level will decrease survivorship due to increased exposure to predators, but will have little effect on growth. The model simulated hourly movement, mortality, and growth of individual mummichogs (Haas and Deegan, in prep.) on a 50 m x 50 m spatial grid of 1-m<sup>2</sup> cells (using a digital orthoquad of Sweeney Creek as the base and projected marsh area change) for 14 days for a cohort of 500 mummichogs. Each fish was assigned an initial length ( $30 \pm 2.5$  mm), baseline growth ( $1 \pm 0.25$  mm d<sup>-1</sup>) and mortality ( $0.0003\% \text{ h}^{-1}$ ) from a normal distribution. To simulate fish movement from creeks onto and across the marsh, fish consider the cells within 1m, then within 2 m, of their current position and moved to the shallowest, yet still inundated, cell in their neighborhood. Predation and growth were then calculated hourly depending on fish position and habitat (predation in open water was 1.75 and in marsh 0.5 times baseline; growth in marsh was 1.25 times baseline).

**<sup>15</sup>N Tracer Flow Model** (arrows proportional to <sup>15</sup>N flow as a % of daily <sup>15</sup>N input)

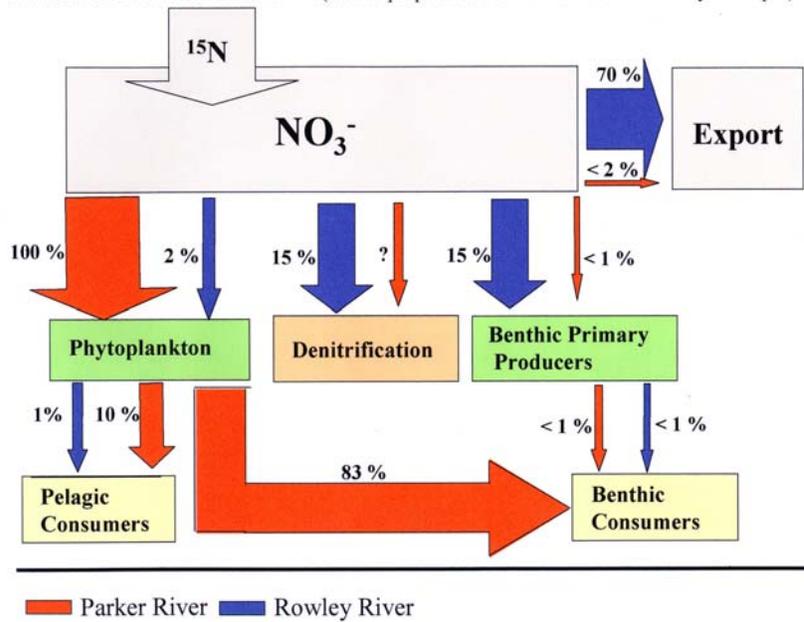


Fig 2.29. <sup>15</sup>N tracer additions are an effective means of delineating foodweb structure and of describing N biogeochemistry. These results contrast the different fates of added <sup>15</sup>N-NO<sub>3</sub><sup>-</sup> to systems with contrasting hydrologic templates – the Parker with long water residence time and the Rowley with short residence time. Note that 100% of the added N was incorporated into a phytoplankton bloom in the Parker, whereas in the Rowley the major autotrophic uptake was by benthic microalgae. <sup>15</sup>N addition experiments are planned for the tidal creeks long-term experiment.

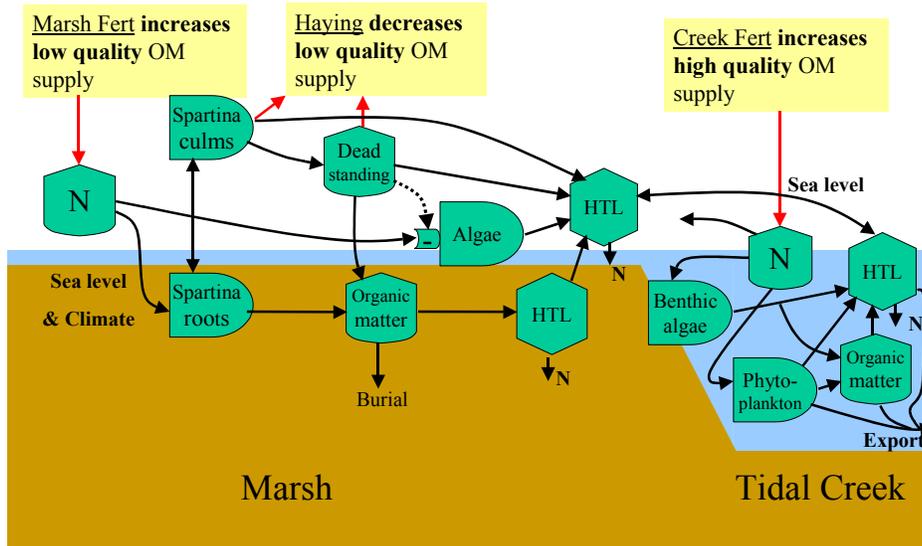


Fig 2.30 Four long-term experiments are designed to test our hypothesis about the interactions of inorganic nutrients and organic matter and foodweb structure. The marsh fertilization experiment in effect increases the supply of low quality organic matter, the haying, or detrital removal experiment decreases the supply of low quality OM, and the tidal creek and sewage addition experiments increase the supply of high quality OM via the stimulation of benthic microalgal production.

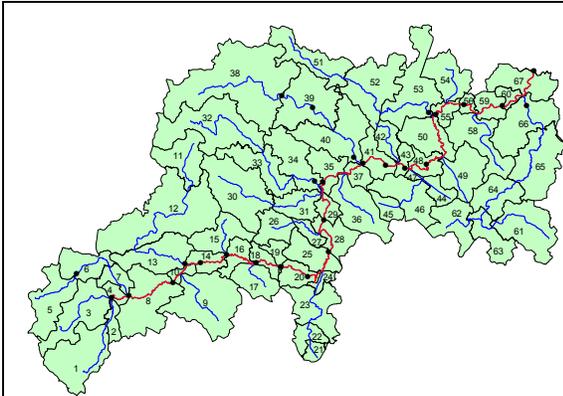


Fig 2.31. Representation of Ipswich watershed in HSPF illustrating 67 sub-basins (black lines and numbers), main stem of Ipswich River (red line) and major tributaries (blue lines).

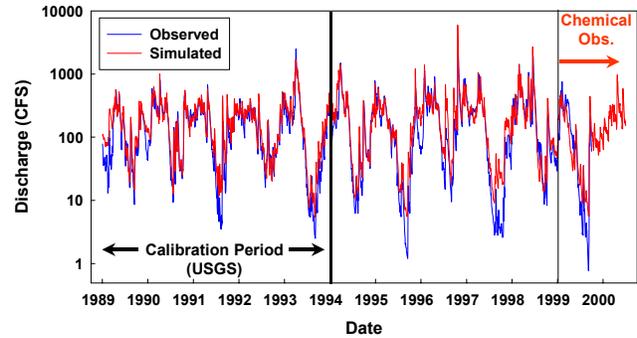


Fig 2.32. Observed (blue) and simulated (red) Ipswich River discharge. Model was calibrated using data from 1989 to 1994.

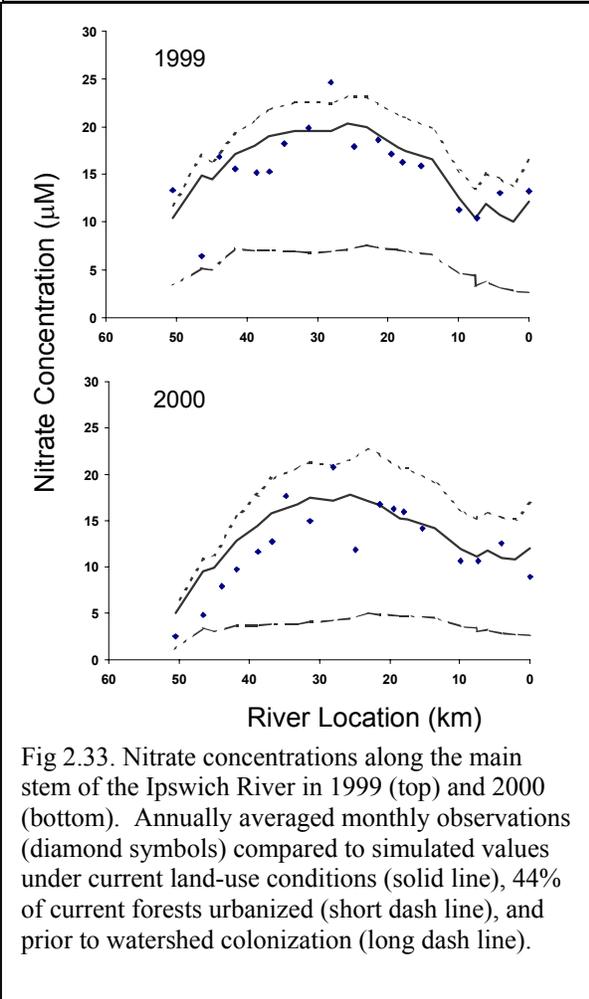


Fig 2.33. Nitrate concentrations along the main stem of the Ipswich River in 1999 (top) and 2000 (bottom). Annually averaged monthly observations (diamond symbols) compared to simulated values under current land-use conditions (solid line), 44% of current forests urbanized (short dash line), and prior to watershed colonization (long dash line).

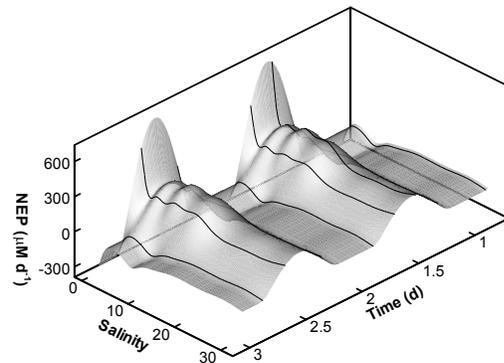


Fig 2.34. Net ecosystem production.

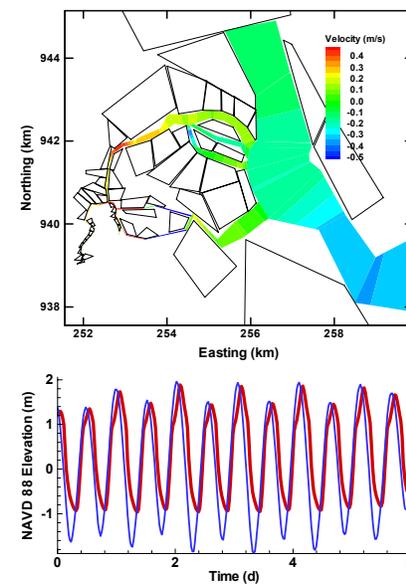


Fig 2.35. Instantaneous tidal velocities (Top) and tidal evaluation at mouth and head of Rowley River (Bottom) from FEQ model. Non-filled polygons are marsh platforms.

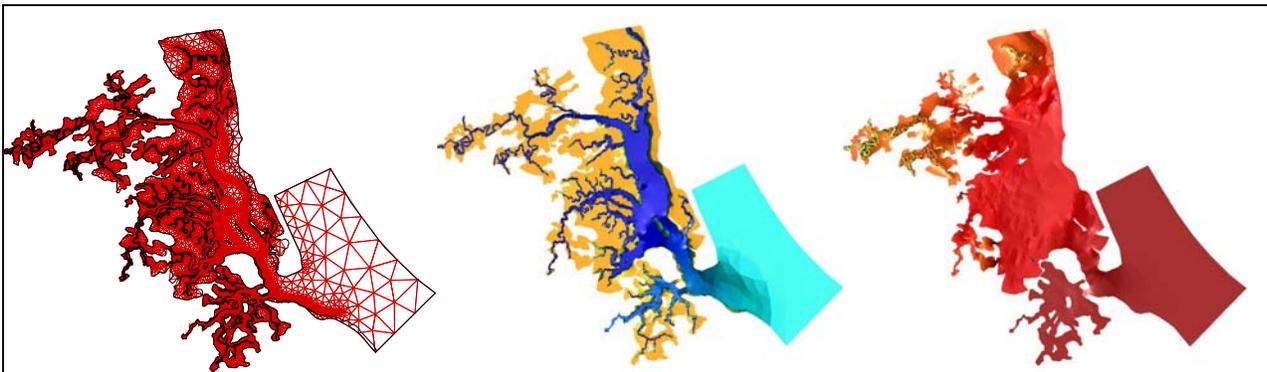


Fig 2.36. Creek resolving finite element grid (left) used in 2D PIE estuarine circulation-biogeochemistry model. Simulated water elevation at low tide (center) and high tide (right).

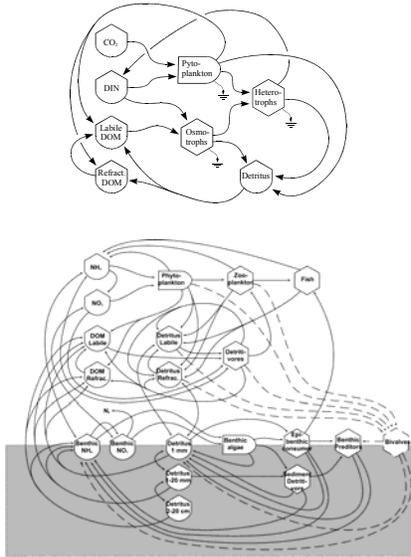


Fig 2.37. Example of simple (top) and complex (bottom) estuarine biogeochemistry models.

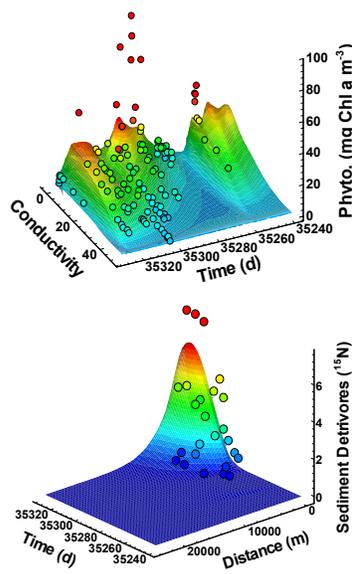


Fig 2.38. Predicted and observed phytoplankton concentration (right) and <sup>15</sup>N incorporation into sediment detritives (left) during Parker River NISOTREX <sup>15</sup>N tracer experiment.

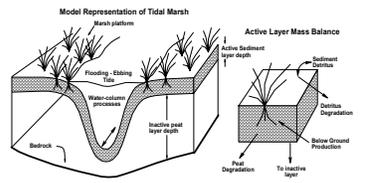


Fig 2.39 Marsh accretion and loss model. Marsh loss or accretion is determined by sediment loading and below ground production.

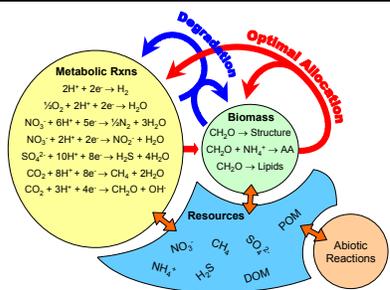


Fig 2.40 Conceptualization of the metabolic biogeochemistry model. Half reactions lead to production of protein (and other building block constituents), which is then allocated to reactions governed by an optimization function. Abiotic reaction can also be incorporated with standard kinetics.

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>). 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
<b>WATERSHED Q1</b> NADP sites (Lexington & Truro, MA)	1	Wet/Dry temperature (T), insolation, precip, wet & dry N/P deposition	Hourly	NADP program
<b>WATERSHED Q1</b> PIE weather station, GDA campus	1	Temp, precipitation, humidity, wind speed/direction, barometric pressure, solar radiation, PAR	15 minute, hourly & daily	Campbell Scientific weather station
<b>WATERSHED Q1</b> NCDC sites (Boston, Groveland, Bedford, Haverill, Lawrence, Marblehead, Middleton, Reading, Ipswich & Newburyport, MA)	1	Temperature, precipitation	Daily	NOAA, National Climatic Data Center
<b>WATERSHED Q1</b> Sub-catchment headwater streams of Ipswich & Parker Rivers	2, 3, 4	Temp, H <sub>2</sub> O level, NH <sub>4</sub> <sup>+</sup> , NO <sub>3</sub> <sup>-</sup> , PO <sub>4</sub> <sup>3-</sup> , DO(N,P,&C) PO(C&N), TSS	Monthly with special storm event sampling	SIGMA autosampler and logger, Alpkem autoanalyzer, UV& high temp oxidation, CHN, gravimetric
<b>WATERSHED Q1</b> Sub-catchment headwater streams of Ipswich & Parker Rivers	2, 3, 4	Total nitrogen and phosphorus	Daily	SIGMA autosampler and logger, Alpkem autoanalyzer, UV& high temp oxidation, CHN, gravimetric
<b>WATERSHED Q1</b> Main rivers, Ipswich, Parker and Rowley Rivers	2, 3	Sedimentation, mineral and organic, depth and mass	Quarterly	Marker horizon depth, plate accumulation, CHN, gravimetric
<b>WATERSHED Q1</b> Export at Ipswich, & Parker dams	2, 3	Temp, NH <sub>4</sub> <sup>+</sup> , NO <sub>3</sub> <sup>-</sup> , PO <sub>4</sub> <sup>3-</sup> , DO(N,P,&C) PO(C&N), TSS, alk, pH	Weekly with special storm event sampling	SIGMA autosampler and logger, Alpkem autoanalyzer, UV& high temp oxidation, CHN, gravimetric
<b>WATERSHED Q1</b> Export at Ipswich & Parker River dams	4	Riverine discharge	Hourly	USGS station
<b>MARSH Q2</b> Parker & Rowley River marshes	1	Macrophyte productivity	Bimonthly- grow season	Phenometric
<b>MARSH Q2 &amp; WATER COLUMN Q3</b> Parker & Rowley River marshes	1	Algal biomass	Monthly - grow season	Pigment analysis

<b>MARSH Q2</b> Parker & Rowley River marshes	2, 3	Accretion	Quarterly	SET tables marker horizons, sedimentation plates
<b>MARSH Q2</b> Parker & Rowley River marshes	2, 3	Organic and ash content	Yearly	Gravimetric, CHN
<b>MARSH Q2</b> Parker & Rowley River marshes	2, 5	Sediment respiration	Yearly	IRGA - custom chamber
<b>MARSH Q2</b> Parker & Rowley River marshes	2, 3, 4	Porewater - $\text{NH}_4^+$ , $\text{NO}_3^-$ , $\text{PO}_4^{3-}$ , DO(C&N) Eh, pH, $\text{S}^{2-}$ , conductivity	Monthly - bimonthly	Diffusion samplers
<b>MARSH Q2</b> Parker & Rowley River marshes	4	Groundwater height	Hourly	Pressure transducers
<b>MARSH Q2</b> Ipswich, Parker & Rowley River marshes and Plum Island Sound	5	Birds	bi-weekly by Audubon and USFWS	direct counts
<b>WATER COLUMN Q3</b> Ipswich, Parker & Rowley Rivers and Plum Island Sound	1, 2, 3, 4, 5	Light, DO, T, cond, $\text{NH}_4^+$ , $\text{NO}_3^-$ , $\text{PO}_4^{3-}$ , DO(N,P,C), PO(C,N), TSS, chl, DO <sub>2</sub> , Prim. Prod & Resp., C&N stable isotopes (DOM, POM, DIC), $\text{DO}^{14}\text{C}$ , $\text{DI}^{14}\text{C}$ , bacteria, zooplankton	quarterly at standard tide	Licor, YSI sondes, autoanalyzer, UV & high temp oxidation, CHN, gravimetric, acetone/fluorescence, O <sub>2</sub> , DIC, IRMS, direct count, net tows
<b>WATER COLUMN Q3</b> Ipswich, Parker & Rowley Rivers and Plum Island Sound	5	Temp, DO, conductivity, turbidity, depth	0.5 hr	YSI water quality sondes
<b>WATER COLUMN Q3</b> Ipswich, Parker & Rowley Rivers and Plum Island Sound	5	Phytoplankton	Yearly	Identification, counts, HPLC pigments
<b>BENTHOS Q4</b> Parker & Rowley Rivers and Plum Island Sound	3, 4	Benthic fluxes	Semi-annually	Core incubations
<b>HIGHER TROPIC LEVELS Q5</b> Ipswich, Parker & Rowley Rivers and Plum Island Sound	2,3	Sediments, benthic diatoms, <i>Nereis</i> , <i>Fundulus</i> , <i>Geukensia</i> , POM, <i>Mytilus</i> , zooplankton, <i>Menidia</i> , <i>Mya</i> , <i>Crassostrea</i>	Yearly	Stable isotopes - IRMS
<b>HIGHER TROPIC LEVELS Q5</b> Ipswich, Parker & Rowley Rivers and Plum Island Sound	5	<i>Fundulus</i> & <i>Menidia</i> dynamics	Yearly	Seine, mark-recapture
<b>HIGHER TROPIC LEVELS Q5</b> Ipswich, Parker & Rowley Rivers and Plum Island Sound	2, 3, 5	Fish	Monthly - season	Seine, trawl, acoustics

Table 2.2. Long-term experiments. Long-term experiments address our hypotheses about the hydrodynamic template and the interaction of nutrients and organic matter in determining the trophic structure, production and efficiency of estuarine food webs. They are also designed to give us a better understanding of plant nutrient limitation and top-down effects on trophic structure and production. Conducting experiments over the long-term enables us to evaluate the secondary effects of climate change, land use change and sea level rise. Lead indicates the PI responsible for coordinating the other researchers in the experiment. **Bold** indicates experiments to be initiated during the next funding cycle. We work in three major marsh types determined by the hydrodynamic template: Fresh marsh dominated by *Typha augustifoli* and saltmarsh dominated by either *S. patens* or *S. alterniflora*.

Experiment	Purpose	Marsh Types	Manipulation	Overview of Measurements
Small-scale N & P marsh enrichment <sup>1</sup> Lead: Morris	Determine plant nutrient limitation in single species marsh plots	Fresh and salt marsh (both types) 1 m <sup>2</sup> plots	Inorganic N and P factorial addition to marsh surface	Plant standing stock and production, porewater nutrients, elevation (SET), sediment and peat accrual
<b>Large-scale N &amp; P enrichment across marsh Ecotones<sup>2</sup></b> Lead: Morris	Increase low quality organic matter inputs & alter plant nutrient limitation and competition leading;	Fresh <b>Salt (both types)</b> 50m x 5m swaths	Inorganic N and P factorial addition to marsh surface	Plant standing stock, species distribution, sediment and peat accrual. Larger plot sizes will enable sampling by more researchers.
Detritus Removal <sup>3</sup> Lead: Buchsbaum	Reduce the input of low quality organic matter	Salt marsh 5 to 10 ha areas	Reference and hayed plots – cut every 2 y.	Plant and animal community structure and standing crop, Sediment and peat accrual
Tidal Creek Nutrient & Water Enrichment <sup>4</sup> Lead: Deegan	Increase the production of organic matter coupled with increased freshwater	Fresh to salt marsh 1 km creek,	Town of Ipswich sewage effluent ~2000 $\mu\text{M NO}_3^-$	Nutrients & chlorophyll Plant and animal community structure and standing crop
<b>TIDE: Tidal Creek Nutrient enrichment and Foodweb manipulation<sup>5</sup></b> Lead: Deegan	<b>Increase the production of organic matter &amp; alter top-down effects on community structure and productivity</b>	<b>8 salt marsh tidal creek watersheds (10 ha each)</b>	<b>Factorial nutrient addition to creek water and fish removal.</b>	<b>Plant and animal community structure and production C, N, P biogeochemistry Sediment and peat accrual</b>

<sup>1</sup> In each of 3 marsh types (*Typha*, *S. alterniflora* and *S. patens*), there are 12 1-m<sup>2</sup> plots. Fertilizer is added 6 times y<sup>-1</sup> to triplicate plots in a factorial design: reference (no fertilizer added), N (30 M NH<sub>4</sub>NO<sub>3</sub> y<sup>-1</sup>), P (15 M P<sub>2</sub>O<sub>5</sub>); and N+P (30 M NH<sub>4</sub>NO<sub>3</sub> and 15 M P<sub>2</sub>O<sub>5</sub>).

<sup>2</sup> At each site, 5 m wide, 50 m long swaths of marsh are fertilized, starting in 100% of one vegetation type, through the transition to another 100% vegetation type. *S. patens* to *Typha* plots were started in 2002. *S. alterniflora* to *S. patens* will be added in 2004. Fertilization treatments are the same as 1.

<sup>3</sup> Detritus removal is accomplished by haying the marsh at the end of the growing season by a local farmer. Haying is rotated among 8 20-ha sections of marsh each year, harvesting each section every other year as per local custom. Twice each season, water column nutrients in adjacent creeks, benthic algae, invertebrates, fish abundance, and marsh plant species composition, biomass and C:N ratio are measured.

<sup>4</sup> The Town of Ipswich discharges freshwater sewage (2000  $\mu\text{M NO}_3^-$ ) into a salt marsh tidal creek, approximately 1500 m long with a marsh area of about 10 ha. Marsh type varies from mixed fresh marsh near the discharge point to salt marsh. We have established 10 50-m transects starting in the creek bottom and moving up onto the marsh platform along the length of the creek. Twice in the growing season, at each transect, water column nutrients, benthic algae, invertebrates, fish abundance, and marsh species composition, biomass and C:N ratio are measured.

<sup>5</sup> The TIDE experiment consists of 8 creeks with 10 ha watersheds, with replicate reference, high nutrient, and fish removal only, and nutrient and fish removal treatments. Nutrients are added on flooding tides to achieve moderate levels of water column enrichment (100  $\mu\text{M NO}_3^-$  and 20  $\mu\text{M PO}_4^-$ ). Each watershed has 5 transects distributed from the headwaters to the mouth of the creek. At each transect, in creek habitats (channel, and mudflat) and marsh types (*S. alterniflora* and *S. patens*), water column nutrients, porewater nutrients, benthic algae, invertebrates, fish abundance, microbial activity, biogeochemical processes and marsh species composition, biomass and C:N ratio are measured. SETs and marker horizons measure sediment inputs. This experiment has received NSF funding under the Integrated Research Challenges in Environmental Biology Program (See web page:

<http://ecosystems.mbl.edu/Tide/>) allowing us to bring in other expertise.

## SECTION 3: SITE MANAGEMENT

### GOVERNANCE

Overall direction and management are provided by Charles Hopkinson with the participation of the other Principal Investigators and research assistants. We have no formal Executive Committee. Research direction, strategic scheduling of major initiatives and budgetary matters are discussed collegially with all PIs (see discussions below) and decisions reached by consensus.

MBL PIs, students, research assistants and postdocs meet at least monthly during the academic year. Non-MBL PI's are invited to attend via phone or in person. These meetings serve to keep everyone aware of progress across all aspects of the LTER, including other projects at Plum Island. Notes are taken and distributed to everyone not able to attend the monthly meetings. In the spring of each year (usually April) we hold a 3-day All-Scientists Meeting in Woods Hole. Scientific, policy and education presentations are given by personnel associated with the LTER and any related projects (see below). At this meeting we synthesize results across disciplines and plan the next year's research agenda. State and local government agencies and non-profit organizations are invited to attend and give presentations. This forum has proven effective for information exchange and learning more about their activities. In addition, subgroups of researchers meet throughout the year in Woods Hole, the field station, and at national meetings to work on research and education projects. It is important to note that 6 of the 11 PIs have offices within 10 m of each other and that Vörösmarty, Mather and Buchsbaum frequently visit MBL.

### COORDINATION

Coordination is organized around the six Programmatic Areas:

<b>Programmatic Area</b>	<b>Coordinator</b>
1) Watersheds	Vörösmarty
2) Marshes	Morris
3) Planktonic	Hobbie/Peterson
4) Benthic	Giblin
5) Higher Trophic Levels	Deegan
6) Synthesis & Modeling	Vallino

Beginning in year 3 (of the renewal), Peterson will assume responsibility for coordinating research in the planktonic programmatic area. Hobbie will continue to remain active in the research program but will not have the responsibility of coordinating this component of our research program. Buchsbaum is involved in many aspects of watershed and estuarine research and his Mass Audubon job is actively engaged in coordination with state government agencies. He also serves as a contact point between PIE and the Mass Audubon educational program. Long-term experiments (Table 2.2) that require involvement across programmatic areas have their own coordinators: 1) Small-scale N and P marsh fertilization – Morris, 2) Large-scale marsh fertilizations – Morris, 3) Detritus Removal Experiment – Buchsbaum, 4) Nutrient and freshwater addition experiment- Deegan, 5) Tidal Creek Fertilization and Fish removal – Deegan.

## **PI ADDITIONS**

We add Gil Pontius (Clark University) and Martha Mather (University of Massachusetts) to the LTER project with this renewal. Pontius has been involved for the past 4 years obtaining support from the EPA funded Water and Watersheds Project in the Ipswich River watershed and from the LTER to supervise REU students. Gil brings a “social science” background to our program and expertise in GIS and dynamic modeling of land use change. Mather has extensive expertise in working with commercially and recreationally exploited fishes, especially herring and striped bass. She has had on-going research in PIE for 4 years (funded by MA Division of Marine Fisheries) and two of her graduate students completed a thesis on core PIE Higher Trophic level questions. Mather brings tighter connections with applied fisheries management agencies. Addition of additional Principal Investigators is determined by consensus.

## **FIELD FACILITY**

Our field facilities were upgraded substantially in early 2003 with MBL’s purchase of Marshview Farm in Newbury, MA (<http://ecosystems.mbl.edu/Tide/marshview.htm>). The facility is on the Parker River, immediately adjacent to the Plum Island estuary and marshes, and within easy driving distance (2-3 miles) of most estuarine field sites. This 5-acre property has a double house and separate large barn. The houses have been retrofitted to house 13 scientists. The basement was transformed into a basic wet and dry laboratory, with balances, refrigerators, freezers, etc. We just received funding from the NSF to plan the remodeling of this facility to meet our growing housing, laboratory, and education needs. We continue to rent the Rowley field house, which has accommodations for 8 additional scientists and some laboratory space. The Rowley house is within walking distance of many of our marsh research sites and has 24/7 boat access to the estuary (dock space for 3 boats on the Rowley River). Our day-to-day coordination of the field site is through our in-house web site that includes a reservation system for boat and field house use.

## **COORDINATION WITH OTHER PROJECTS**

The PIE LTER is the umbrella project for a portfolio of grants with goals complementary to the LTER (see budget justification). These include: Microbial Observatory (Hobbie PI), benthic biogeochemistry (SeaGrant Gibling PI), intersite comparison of stream N cycling (NSF LINX II Peterson co-PI), coastal estuarine indicators including marsh geomorphology (EPA Morris PI), tidal creek fertilization and fish removal (NSF Deegan PI), land use change in Massachusetts (NSF Pontius PI), and continental scale hydrology (NASA Vörösmarty PI). There are many other projects at least partly conducted at the site that provide us with information critical to understanding the function of coastal ecosystems. The primary mechanism we use to communicate across this myriad of projects is the annual All Scientists Meeting in Woods Hole where all projects present their results and future plans.

We encourage others to use the LTER site by giving presentations at local, state, national and international meetings; our web page; a policy of open data via our website and LTER database; by working with non-LTER scientists to develop research proposals; and by leading field trips to colleges and universities in the region. We also write letters of support for investigators seeking funds to conduct research at PIE. To date we have provided free housing and laboratory facilities to everyone seeking to conduct research at the site.

## **SECTION 4: INFORMATION MANAGEMENT AND TECHNOLOGY**

### **DESCRIPTION OF DATA INFORMATION AND 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 easily accessible to PIE-LTER scientists, local, regional, 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 Windows 2000 network server, which is backed up on tape nightly. Public access to PIE-LTER data and information for the scientific community at large is provided through the PIE-LTER World Wide Web home page on the Internet at the following URL: <http://ecosystems.mbl.edu/PIE>. Near real time water quality and weather data are also available on our field station website, [www.pielter.org](http://www.pielter.org). The PIE-LTER home page has been active since late 1998 and contains information on personnel, data and published and unpublished papers and reports. 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.

### **DATA MANAGEMENT AND COORDINATION OF RESEARCH PROGRAMMATIC AREAS**

The information management team consists of: Chuck Hopkinson (Lead PI), Joe Vallino (PI), Robert (Hap) Garritt (IM), Gil Pontius (PI) and one additional research assistant. 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 22 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 six core programmatic areas outlined in the PIE-LTER (Watersheds, Marshes, Planktonic Food Web, Benthos, Higher Trophic Levels and Synthesis). 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 access policy defined on the LTER web page, <http://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. Individual researchers will be 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 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 WWW 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 access policy for the LTER network that states:

“There are two types of data: Type I (data that is freely available within 2-3 years) with minimum restrictions and, Type II (Exceptional data sets 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, state partners and the broader scientific community, as we have no registration requirements for either observing or downloading data from our WWW page, which results in unobstructed access to all PIE LTER databases. Access to PIE data on the WWW 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. However it is possible for users to download data without sending notification. We believe that unobstructed access to our data will encourage users to browse our WWW page and become involved with our research.

On-line PIE LTER data set usage is represented in Table 4.1 and Figure 4.1. Researchers at PIE do get requests via email and phone for particular data sets, but since we have no formal registration, we have no formal documentation of the requests. However, analyses of PIE Web server log files, after removing web spiders, indicates that our on-line data sets are viewed extensively. On average during 2003 PIE had more than 20,000 hits/month on our home page, more than 4,000 hits/month on our Programmatic Area data pages, and more than 400 hits/month on our Field Station homepage. Approximately 50 -70% of the usage was derived from the Marine Biological Lab (PIE associated) domains and the remaining from users not associated with the PIE LTER program. Educational user groups dominated with 69% of the usage followed by non-government (23%), foreign, representing 89 countries (6%) and government (2%).

#### **NETWORK PARTICIPATION**

The PIE LTER program participates in the annual LTER Information Managers meetings, contributes to network level databases of ClimDB, HydroDB, Personnel, Bibliography and Data Table of Contents and has been involved with LTER Network EML workshops. At the 2000 LTER All Scientists Meeting, Hap Garritt helped organize a workshop on Ecological Informatics: Innovative Tools and Technologies.

## **FUTURE OBJECTIVES**

The PIE LTER tries to be inclusive with regard to all data associated with PIE being made available on the WWW. However we typically have problems getting complete and fully documented data from students. We have managed to get presentations, typically Microsoft Power Point files, which we post on the web. Students (mostly REUs) usually have very limited amounts of time for completion of their summer projects and have not made it a priority once their projects are completed to compile their data and metadata in the proper formats. In the future we will stress to students that it is a requirement of their internships to submit their project data and metadata before departing for the summer.

PIE is planning on creating Ecological Metadata Language (EML) metadata from our existing structured text based metadata. EML is a metadata standard based on the XML Schema specification and has been chosen by the LTER Network as the new metadata standard. The LTER network office is helping the PIE LTER with the conversion by developing software tools for generating EML compliant metadata from our text-based metadata. We plan on storing the EML metadata in Metacat, an XML metadata database at the LTER network office, which will allow for automated searching and retrieval of metadata information. Web style sheets will be developed for viewing the EML metadata, but we are also planning on continuing to generate text-based metadata during the transition to EML.

Our collaboration with Gil Pontius and students from Clark University has generated extensive spatial data sets for the Ipswich watershed. Clark's spatial data is generated in IDRISI and PIE's spatial data is generated in ArcView 3.X and ArcGIS. While we are continuing to integrate Clark's spatial data with our information system using third party extensions in ArcView 3.1x to convert the data into a form compatible with the latest version of ArcGIS, we are also investigating other options for compatibility. Other options include: 1) Pontius converting IDRISI data prior to distribution to PIE, 2) PIE buying IDRISI and 3) while ArcGIS does not have an import capability, one could theoretically be developed in Visual Basic for Applications (VBA), the scripting language for ArcGIS. We will also be addressing the compatibility of metadata and how to convert IDRISI and ArcView/ArcGIS metadata into the new EML.

Table 4.1. Monthly use of the PIE LTER Web Site during 2003 summarized from analyses of the PIE Web server log files. Use is represented as the number of times a web page has been accessed (Hits).<sup>a</sup>

Year 2003	Hits on PIE Homepage		Hits on PIE Programmatic area data		Hits on Field-Station Homepage	
	MBL Domain	Non-MBL Domain	MBL Domain	Non-MBL Domain	MBL Domain	Non-MBL Domain
JAN	14,907	8,922	2,413	1,548	37	85
FEB	10,054	9,649	2,018	1,700	32	88
MAR	10,859	9,619	2,138	1,511	112	138
APR	10,051	11,676	2,098	1,695	418	196
MAY	10,714	11,649	2,312	2,123	494	150
JUN	10,077	10,281	1,964	1,846	451	161
JUL	10,075	9,593	2,016	1,276	404	201
AUG	10,009	8,143	2,003	1,267	444	115
SEP	9,492	12,937	2,179	1,990	457	149
OCT	20,307	15,038	4,468	2,529	445	119
NOV	17,639	11,529	3,179	2,113	228	144
DEC	10,163	10,019	2,237	1,734	10	36
Annual Total	144,347	129,055	29,025	21,332	3,532	1,582

<sup>a</sup>Web spider hits have been excluded.

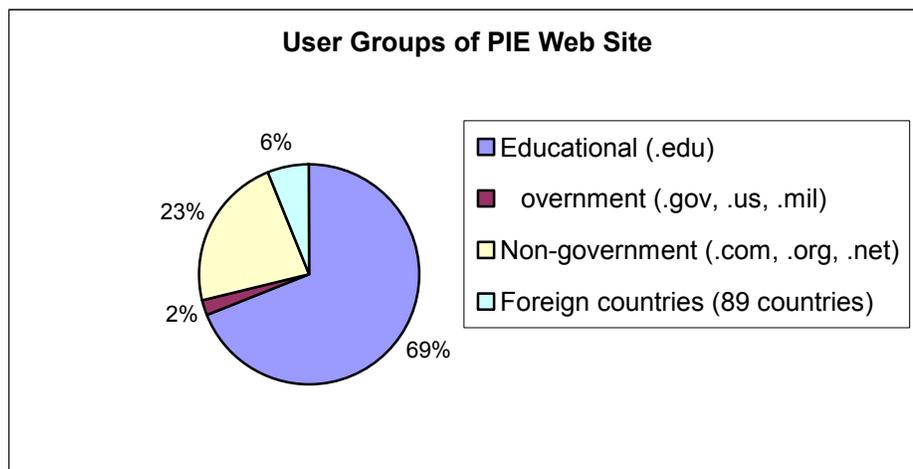


Fig 4.1. User groups of the PIE LTER Web Site during 2003.

## SECTION 5: OUTREACH AND EDUCATION PROGRAMS

The PIE LTER has developed links with local teachers and students, citizens, conservation organizations, and local, state and federal agencies. What started out as a “minimalist” program has grown to be a broad, well-rounded suite of activities. We expect our education/outreach program to further expand during LTER2, as we actively seek additional support from other federal agencies, the Commonwealth of Massachusetts, and private foundations. Our long-term goal is to establish a “Coastal Outreach” office at our study site that would serve to integrate and promote our interactions with interested parties throughout New England, similar to the Hubbard Brook Research Foundation.

### EDUCATION

Our goals are to: 1) excite kids and teachers about coastal science, 2) to train the next generation of scientists, 3) to develop an environmentally conversant citizenry, and 4) inform the local stakeholders about our LTER-related research.

#### Schoolyard Program

This program has been very successful as a result of collaboration with Massachusetts Audubon Society and Governor Dummer Academy and additional NSF funds (Schoolyard and the EHR Environmental Education supplements). Teachers at Governor Dummer Academy, especially Susan Olezsko, have developed science modules for high school students using student monitoring of ribbed mussels and intertidal marsh plant distribution. The approach and methods were developed in conjunction with LTER scientists and the data are included in the PIE database and website (<http://ecosystems.mbl.edu/pie/data/student/schlyard.htm>). The MA Audubon Society has implemented, with partial support from the LTER, a 4<sup>th</sup>–12<sup>th</sup> grade science education program, “The Salt Marsh Science Project,” ([http://www.massaudubon.org/Kids/Lively\\_Lessons/Saltmarsh/index.html](http://www.massaudubon.org/Kids/Lively_Lessons/Saltmarsh/index.html)). This program focuses on the invasion of *Phragmites australis* in salt marshes. Transects are set up near schools and analyzed for long-term (now over 8 years of data in some sites) changes in vegetation, pore-water salinities and fish use. The additional NSF funds have increased the number of students by 50% (n~1500) and the number of teachers by 20% (n=42). During LTER2 we will develop new programs to provide on-going professional development for teachers; support the expansion of this project into nearby urban areas including Salem, Boston, and Revere; and facilitate the transfer of this program to New Hampshire and Maine via the Gulf of Maine Institute.

#### Undergraduate Education

Undergraduates have been an important focus of our LTER (Table 5.1). We involve undergraduates in many ways: research internships and senior theses, guest lectures at home institutions, field trips, research collaborations with undergraduate institution faculty and new LTER-based curriculum. We annually sponsor 4-7 REU students who often use this for a Senior Thesis. We involve non-LTER scientists from small colleges by having them be primary advisor to LTER REU students. Sallie Sheldon, Middlebury College, is a good example. She supervised an REU one summer and used this data to obtain a NSF Research Opportunity Award (including 2 undergraduates) that enables her to continue her collaboration. We pride ourselves on the success of our REU students in publishing their research (asterisks in PIE bibliography). We often lecture and take part in field trips for local

colleges (e.g., Wellesley, Brandeis, UMass Lowell). In our own undergraduate program (MBL Semester in Environmental Science) we use PIE as a field laboratory and the data in our lectures.

### **Graduate and Post-Graduate Education**

We have three levels of involvement: 1) graduate students and postdocs associated with the core LTER PIs and project (UNH, USouthCarolina, Clark, UMass, MBL); 2) grad students associated with scientists involved in other funded research at Plum Island tightly related to LTER goals (e.g., LSU, VIMS, Yale, UMD, WHOI, MIT, UWash); 3) grad students and postdocs conducting their research at the PIE site using LTER data and logistical support but not necessarily closely related to LTER goals (e.g., WHOI, MIT). We have had 57 graduate students and postdoctoral associates associated with the LTER (Table 5.1). The expansion of our field station facilities and a new educational partnership between MBL and Brown University will allow us to significantly expand our involvement in Ph.D. graduate education.

### **OUTREACH**

Our goal is to communicate our findings to individuals, organizations, and agencies that will use our research results to better manage local and regional coastal resources. We have established partnerships on three major issues: intertidal marshes, coastal eutrophication and watershed resource management (Table 5.2). Our interactions range from LTER scientists giving public lectures (e.g., ‘Why does the Ipswich River run dry?’) to serving on the MA Executive Office of Environmental Affairs Task Force on Watershed Management, to working with the Town of Ipswich to evaluate the impacts of their sewage effluent. Our annual ‘All Scientists Meeting’ has been an excellent way to get our information to our partner organizations and government agencies. An EPA-funded grant established a partnership between the Town of Ipswich, MBL, UNH, local watershed associations, state agencies, and the USGS to improve monitoring of inland waters. Ipswich and Parker River Watershed Association volunteers helped take samples in a spatially-extensive stream sampling program and a public outreach component via a web site with live broadcast of results (The Ipswich-Parker Suburban Watershed Channel - devoted to water flow and quality issues; see [www.ipswatch.sr.unh.edu](http://www.ipswatch.sr.unh.edu)). We continue to work with the civic associations to maintain an active volunteer constituency.

The issues of sea level rise, marsh survival and wetland restoration will be the next outreach focal points. We have found some evidence that that Plum Island marshes are sinking relative to sea-level rise. Understanding the reasons for this is a focus of some of the proposed research (Question 3 and the long-term tidal creek fertilization experiment). Once we understand the causes, however, deciding what to do (if anything) will be a societal decision. We find it interesting that various stakeholders have different perspectives on the value of marshes in different conditions. For example, degraded marshes with their abundance of marsh ponds offer prime habitat to many waterbirds, however such marshes do not offer the same level of storm protection as intact marshes. In the future the LTER will help local and state agencies understand the consequences to the marsh of sea level rise and nutrient enrichment and enable them to respond in the way that maximizes societal benefits.

Table 5.1. Students who have been involved with PIE LTER research via PhD and Masters programs or Undergraduate REUs, internships and special research projects or High School projects.

	Educational Degree				
	Post Doc	PhD	MS/MA	BS/BA	HS
<b>Completed</b>	15	10	17	33	13
<b>Ongoing</b>	1	11	3	9	3

Table 5.2. Outreach partners that the PIE LTER is collaborating with on a variety of societal and scientific issues.

Societal Issue	Civic Organizations, NGOs and Local Agencies	Massachusetts State Agencies	Federal Agencies
<b>Sea Level Rise</b>  <b>Wetland Restoration</b>  <b>Wetland Survival</b>	Mass Audubon Society  Essex County Greenbelt Association (ECGA)  Nature Conservancy	Dept of Environmental Protection (DEP) Executive Office of Environmental Affairs (EOEA) Coastal Zone Management (CZM) Dept of Fish and Game Mass Geographic Information System (Mass GIS) Wetlands Restoration Program	NRCS – Westford Service Center USFWS National Wetlands Inventory (NWI) Parker River National Wildlife Refuge USEPA - Atlantic Ecology Division (AED) + Environmental Monitoring and Assessment Program (EMAP)
<b>Sewage Effluent Discharge</b>  <b>EUTROPHICATION</b>	Ipswich River Watershed Association (IRWA) Parker River Clean Water Association (PRCWA) Island Futures Group Towns of Ipswich, Rowley, Newburyport	DEP EOEA Dept of Conservation Resources (DCR) Water Resources Commission Mass Bays Program Division of Marine Fisheries	USEPA – Atlantic Ecology Division (AED)
<b>Low River Flow</b>  <b>River Restoration, Dam Removal and Beavers</b>  <b>Land Use Change and “Smart Growth”</b>	IRWA PRCWA Horizon Foundation Essex County Community Foundation Audubon Society ECGA Nature Conservancy Town of Ipswich	EOEA  DEP  DCR  Mass GIS  Water Resources Commission	USGS  USEPA – AED  NRCS

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#### **BOOK SECTIONS**

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Table 1.2 Data sets available on PIE LTER WWW site, <http://ecosystems.mbl.edu/pie>. On-Line Status, (O) for available, (P) for pending. Documentation of on-line data access is available in Section 4, Table 4.1.

Dataset	Dataset Title	Lead PI	Begin Year	End Year	On Line Status
<b>WATERSHEDS</b>					
WATsite	Watershed sampling site locations	Vorosmarty	1993	present	O
WAT-VA-Inputs	Water chemistry of the Ipswich & Parker Rivers	Vorosmarty	1993	2003	O
WAT-VA-Stream Nutrients	Rain event nutrient time course for 8 streams	Hopkinson	1992	1993	O
WAT-PR-Parker Discharge 01101000	Parker River discharge @ Byefield, MA	Vorosmarty	1945	2001	O
WAT-IP-Ipswich Discharge 01102000	Ipswich River discharge near Ipswich, MA	Vorosmarty	1930	2001	O
WAT-IP-Ipswich Discharge 01101500	Ipswich River discharge near S. Middleton, MA	Vorosmarty	1938	2001	O
WAT-IP-Catchments	Nutrients of Ipswich River, 1st to 4th order catchments	Hopkinson	1999	2000	O
WAT-IP-1998 Monthly	Nutrients of Ipswich River main stem, major tributaries	Hopkinson	1998	1999	O
WAT-IP-Monthly Sampling	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-VA-SigmaDailyNutrients	Daily nutrients from Sigma auto samplers in various watershed locations	Hopkinson	2001	present	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_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-MBL-IP-catchments	Nutrients of Ipswich River, 1st to 4th order catchments, to standardize IDs	Hopkinson	2000	2002	O
WAT-UNH-IP-catchments	Nutrients of Ipswich River headwaters with IRWA volunteer help	Vorosmarty	2001	2002	O
WAT-UNH-PR-catchments	Nutrients of Parker River headwaters with PRCWA volunteer help	Vorosmarty	2001	2002	O
WAT-YSI-SIGMA-timeseries	Nutrient grab samples from 6 sites of the Ipswich and Parker Rivers	Vorosmarty	2001	2002	O

<b>Dataset</b>	<b>Dataset Title</b>	<b>Lead PI</b>	<b>Begin Year</b>	<b>End Year</b>	<b>On Line Status</b>
<b>MARSH</b>					
MARsite	Marsh sampling site locations	Morris	1998	present	O
MAR-RO-Transects	Marsh vegetation along 5 transects on the Rowley River	Hopkinson	1998	1998	O
MAR-RO-Sedimentation	Sedimentation along five transects on the Rowley River	Hopkinson	1998	1998	O
MAR-RO-Porewater	Porewater nutrients (Rowley, Parker Rivers, MA) (Wells, ME)	Morris	1998	2001	O
MAR-EX-ArgRMTr	Marsh transect physical layout on Argilla Rd and Rough Meadows	Buchsbaum	2001	2001	O
MAR-EX-ArgRMVeg	Plant species presence in Argilla Rd and Rough Meadows marsh	Buchsbaum	1995	2000	O
MAR-PR-Wtable-RRA-2001	Water table heights at the railroad Spartina marsh on Parker River	Morris	2001	2001	O
MAR-PR-Wtable-RRB-2001	Water table heights at the railroad Spartina marsh on Parker River	Morris	2001	2001	O
MAR-PR-Wtable-RRA-2002	Water table heights at the railroad Spartina marsh on Parker River	Morris	2002	2002	O
MAR-PR-Wtable-RRB-2002	Water table heights at the railroad Spartina marsh on Parker River	Morris	2002	2002	O
MAR-PR-Wtable-TA-2001	Water table heights in Typha marsh on the Parker River	Morris	2001	2001	O
MAR-PR-Wtable-TB-2001	Water table heights in Typha marsh on the Parker River	Morris	2001	2001	O
MAR-PR-Wtable-TA-2002	Water table heights in Typha marsh on the Parker River	Morris	2002	2002	O
MAR-PR-Wtable-TB-2002	Water table heights in Typha marsh on the Parker River	Morris	2002	2002	O
MAR-RO-MarkerHorriizon	Marsh sediment marker horizon data from Rowley marshes	Morris	2002	present	O
MAR-RO-SET	Marsh platform SET data from Rowley marshes	Morris	2002	present	O
<b>WATER COLUMN</b>					
ESTsite	Parker River estuarine transect locations	Hopkinson	1994	present	O
EST-PR-O2	Parker River Plum Island Sound, dawn & dusk metabolism transects	Hopkinson	1995	2001	O
EST-PR-NUT	Parker River Plum Island Sound, water chemistry transects	Hopkinson	1994	2003	O
MONsite	Long-Term Monitoring site locations	Hopkinson	2000	present	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	P
MON-PR-RT1AYSIS2000	Year 2000 YSI continuous water quality data, Parker River, Rt1A	Hopkinson	2000	2000	O
MON-PR-RT1AYSIS2001	Year 2001 YSI continuous water quality data, Parker River, Rt1A	Hopkinson	2001	2001	O
MON-PR-RT1AYSIS2002	Year 2002 YSI continuous water quality data, Parker River, Rt1A	Hopkinson	2002	2002	O

<b>Dataset</b>	<b>Dataset Title</b>	<b>Lead PI</b>	<b>Begin Year</b>	<b>End Year</b>	<b>On Line Status</b>
MON-PR-RT1AYSI2003	Year 2003 YSI continuous water quality data, Parker River, Rt1A	Hopkinson	2003	2003	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	P
<b>BENTHOS</b>					
BENsite	Benthic sediment sampling locations	Giblin	1993	present	O
BEN-PR-Flux	Benthic metabolism and nutrient cycling in Parker & Rowley Rivers	Giblin	1993	2003	O
BEN-PR-Sediment	Benthic sediment porewater chemistry in Parker & Rowley Rivers	Giblin	1993	1999	O
<b>HIGHER TROPHIC LEVELS</b>					
HTLsite	Higher trophic level sampling locations	Deegan	1993	present	O
HTL-SO-Bird	Decade average counts for selected birds in Plum Island Sound	Buchsbaum	1930	2000	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-PIE-Yearly Isotope Survey	Annual stable isotope functional group surveys	Deegan	1999	2003	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
<b>LONG TERM EXPERIMENTS</b>					
LTE-TC-site	Long-term tidal creek fertilization sites	Deegan	1998	present	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-site	Long term marsh detritus removal (hay) sites including frequency	Buchsbaum	2000	present	O
LTE-MD-VEGSTN	Physical layout of sites in hayed and reference areas	Buchsbaum	2000	2000	O

Dataset	Dataset Title	Lead PI	Begin Year	End Year	On Line Status
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-EOYBIOM2000	Vegetation biomass & cover, end of season at hayed and reference sites	Buchsbaum	2000	2000	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-MP-SET	Summarized sediment elevation table data from marsh fertilized plots	Morris	1999	2001	O
LTE-MP-SETraw	Raw sediment elevation table data from marsh fertilized plots	Morris	1999	2001	O
LTE-MP-LPPbiomass	Vegetation biomass from Spartina patens marsh fertilized plots	Morris	1999	2001	O
LTE-MP-LPAbiomass	Vegetation biomass from Spartina alterniflora marsh fertilized plots	Morris	1999	2001	O
LTE-MD-EOYBIOMASS	Vegetation biomass & cover, end of season at hayed and reference sites	Buchsbaum	2000	2001	O
LTE-EX-ARGILLA RM PHRAGHEIGHTS	Phragmites heights at Argilla Rd and Rough Meadows marshes	Buchsbaum	1997	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 VEGSTN	Vegetation transect physical layout on Argilla Rd and Rough Meadows	Buchsbaum	1995	2002	O
LTE-EX-ARGILLA RM VEGTRANS	Plant species presence in Argilla Rd and Rough Meadows marsh	Buchsbaum	1995	2002	O
LTE-MD-EOYBIOMASS	Vegetation biomass & cover, end of season at hayed and reference sites	Buchsbaum	2000	2001	O
LTE-MF-GREENWOOD CLUBHEAD EOY BIOMASS	Vegetation biomass & cover, end of season at enriched and reference sites	Buchsbaum	2002	2002	O
LTE-MF-GREENWOOD CLUBHEAD VEGQUADS	Plant species percent cover at enriched and reference sites	Buchsbaum	2002	2002	O
LTE-MF-GREENWOOD CLUBHEAD VEGSTN	Vegetation transect physical layout at the enriched and reference sites	Buchsbaum	2002	2002	O
LTE-MF-GREENWOOD CLUBHEAD VEGTRANS	Vegetation percent frequency at the enriched and reference sites	Buchsbaum	2002	2002	O
<b>SHORT TERM EXPERIMENTS</b>					
STP-PR-Mesocosm	Mesocosm experiment testing quality & quantity of DOM on foodwebs	Hopkinson	1994	1994	O
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
<b>SCHOOLYARD</b>					
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

<b>Dataset</b>	<b>Dataset Title</b>	<b>Lead PI</b>	<b>Begin Year</b>	<b>End Year</b>	<b>On Line Status</b>
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
<b>CLIMATE</b>					
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	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-MetHour2003	Year 2003, hourly averages of meteorological station data	Hopkinson	2003	2003	P
MON-PR-MetDay	Daily averages of meteorological station data	Hopkinson	2000	2002	O
MON-PR-MetDay-PIEClimDB	PIE LTER CLIMDB data contributions	Hopkinson	2000	2002	O
MON-VA-NCDC	Climate data from National Climate Data Center	Hopkinson			P
<b>ESTUARINE PHYSICS</b>					
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-PR-MBWATERLEVEL2000	Year 2000, water level data, Middle Road Bridge, Parker River	Vallino	2000	2000	O

<b>Dataset</b>	<b>Dataset Title</b>	<b>Lead PI</b>	<b>Begin Year</b>	<b>End Year</b>	<b>On Line Status</b>
MON-PR-MBWATERLEVEL2001	Year 2001, water level data, Middle Road Bridge, Parker River	Vallino	2001	2001	O
MON-PR-MBWATERLEVEL2002	Year 2002, water level data, Middle Road Bridge, Parker River	Vallino	2002	2002	O
MON-PR-MBWATERLEVEL2003	Year 2003, water level data, Middle Road Bridge, Parker River	Vallino	2003	2003	P
MON-PR-RT1AWATERLEVEL2000	Year 2000, water level data, Rt 1A, Parker River	Vallino	2000	2000	O
MON-PR-RT1AWATERLEVEL2001	Year 2001, water level data, Rt 1A, Parker River	Vallino	2001	2001	O
MON-PR-RT1AWATERLEVEL2002	Year 2002, water level data, Rt 1A, Parker River	Vallino	2002	2002	O
MON-PR-RT1AWATERLEVEL2003	Year 2003, water level data, Rt 1A, Parker River	Vallino	2003	2003	P
MON-SO-IBYCWATERLEVEL2000	Year 2000, water level data, Ipswich Bay Yacht Club, Plum Island Sound	Vallino	2000	2000	O
MON-SO-IBYCWATERLEVEL2001	Year 2001, water level data, Ipswich Bay Yacht Club, Plum Island Sound	Vallino	2001	2001	O
MON-SO-IBYCWATERLEVEL2002	Year 2002, water level data, Ipswich Bay Yacht Club, Plum Island Sound	Vallino	2002	2002	O
MON-SO-IBYCWATERLEVEL2003	Year 2003, water level data, Ipswich Bay Yacht Club, Plum Island Sound	Vallino	2003	2003	P
<b>GLOBAL POSITIONING</b>					
GPS-VA-Kinematic	Trimble GPS Kinematic surveys	Vallino	1998	present	P
GPS-VA-Static	Trimble GPS Static surveys	Vallino	1998	present	P
<b>GIS &amp; MAPS</b>					
GIS-VA-PIEGIS	Longitude and latitude of various PIE-LTER sampling sites	Hopkinson	1994	present	O
GIS-IP-ip30_info_anderson1_1971	Ipswich watershed land use 1971 according to MassGIS and Anderson Level 1	Pontius	1971	1971	O
GIS-IP-ip30_info_anderson1_1985	Ipswich watershed land use 1985 according to MassGIS and Anderson Level 1	Pontius	1985	1985	O
GIS-IP-ip30_info_anderson1_1991	Ipswich watershed land use 1991 according to MassGIS and Anderson Level 1	Pontius	1991	1991	O
GIS-IP-ip30_info_anderson1_1999	Ipswich watershed land use 1999 according to MassGIS and Anderson Level 1	Pontius	1999	1999	O