

# **PLUM ISLAND ECOSYSTEMS LONG-TERM ECOLOGICAL RESEARCH**

## **3-YR PROGRESS REPORT**



**Prepared for Fall 2007  
National Science Foundation  
Site Review Team Visit**

## MID-TERM REVIEW REPORT – TABLE OF CONTENTS

Introduction and Conceptual Framework .....	1
Program Area Research Summaries	
Q1: Watersheds .....	9
Q2: Marshes .....	14
Q3: Water Column .....	18
Q4: Benthos .....	22
Q5: Higher Trophic Levels .....	27
Integration and Simulation Modeling .....	32
Data and Information Management .....	40
LTER Network Activities .....	44
Education and Outreach .....	47
Site Management .....	52
Literature Cited.....	54

## INTRODUCTION and CONCEPTUAL FRAMEWORK

The Plum Island Ecosystems LTER (PIE LTER) was established in 1998 and renewed in 2003. We have designed and implemented a comprehensive study of a major, land-estuarine system in the Acadian biogeographic province in eastern New England (Fig 1). Our goal is to develop a predictive understanding of the long-term response of watershed and estuarine ecosystems at the land-sea interface to changes in climate, land use and sea level 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. 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 (Crossett et al. 2004) 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 (Crossett et al. 2004); we see similar dramatic increases in population in the Ipswich and Parker River watersheds (Fig 2). 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 3). 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

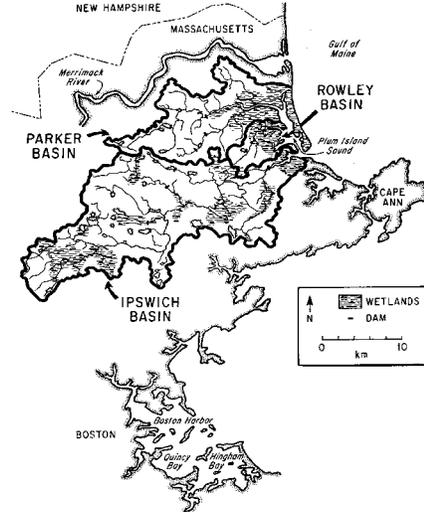


Fig 1. Location of PIE LTER in northeastern Massachusetts.

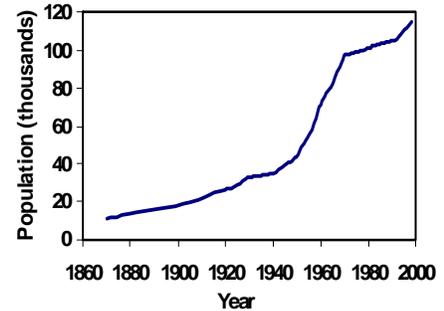


Fig 2. Population growth has occurred in two waves in the Ipswich River basin.

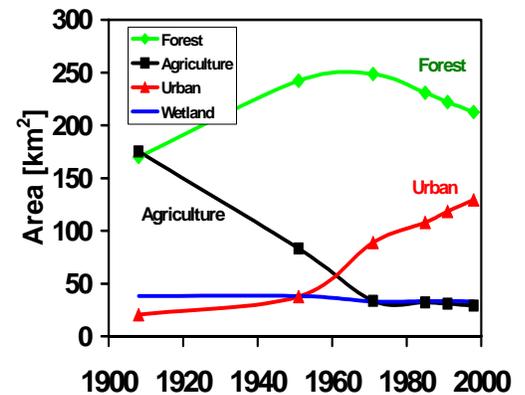


Fig 3. A pattern of agricultural abandonment, reforestation and urbanization have occurred in watersheds of the Plum Island system.

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 4 Claessens et al., 2006). 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 5). 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.

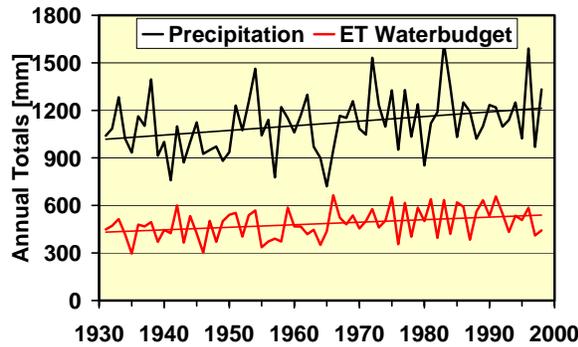


Fig 4. Century-long changes in precipitation and evapotranspiration have been observed in PIE watersheds.

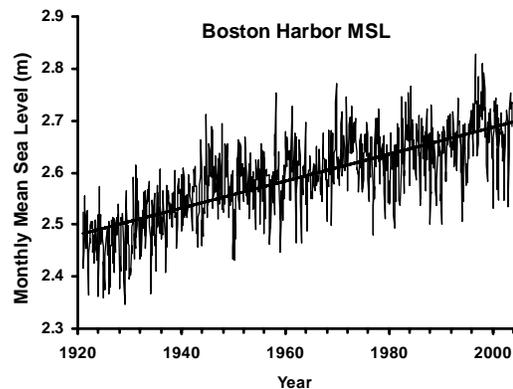


Fig 5. Sea level is rising at about 2.5 mm/yr at PIE

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:

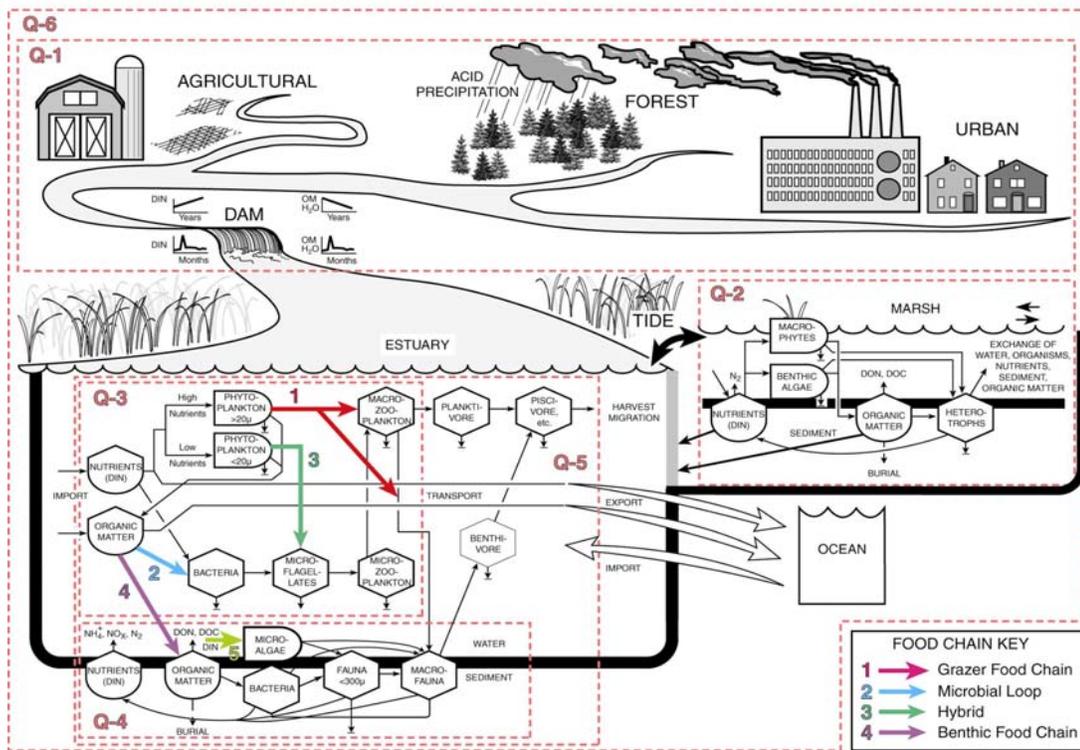
**How will trophic structure and primary and secondary productivity in estuaries be affected by changes in organic matter and nutrient loading and hydrodynamics caused by changing land use, climate and sea level?**

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.**

**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.**

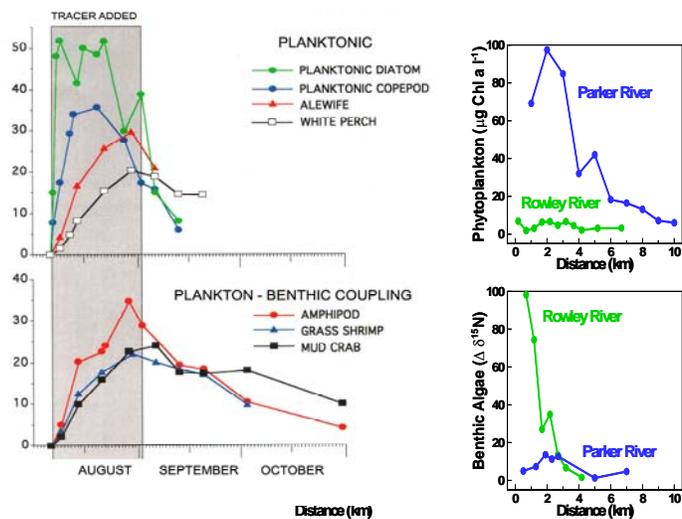
We have a trophic flow model and diagram (Fig 6) to synthesize our understanding of the effects of organic matter and nutrient inputs on trophic structure and function (Deegan et al. 1994). We envision that basic pathways of organic matter and nutrient processing might vary over decadal time scales in relation to long-term changes in the loading of organic matter and nutrients from watersheds. Over the past 9 years our perceptions of how estuarine ecosystems are structured and function have changed substantially. 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).



**Fig 6. Conceptual model showing the 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.**

We find that the most important input of organic matter is the marsh (Raymond and Hopkins 2003) and that there are major recycling sources of DIN internal to the system that are controlled by salinity variations (Giblin et al. submitted). 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 7; Hughes et al. 2000). Benthic microalgal production is often an important base of the foodweb (Fig 7; 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 Hopkins 1998). Residence time of water in the upper estuary decreases from 34



**Fig 7. Isotopic enrichment of pelagic and benthic organisms following 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. Graphs to the right illustrate the importance of water residence time: with long residence time, phytoplankton are the principal primary producers (top right), while when residence time is short benthic algae are the principal autotrophs.**

– 2 d as river flow increases from  $0.01$  to  $10 \text{ m}^3 \text{ s}^{-1}$  (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 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 (Fig 8). 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 find that these “spheres of influence” 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. Figure 8 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.

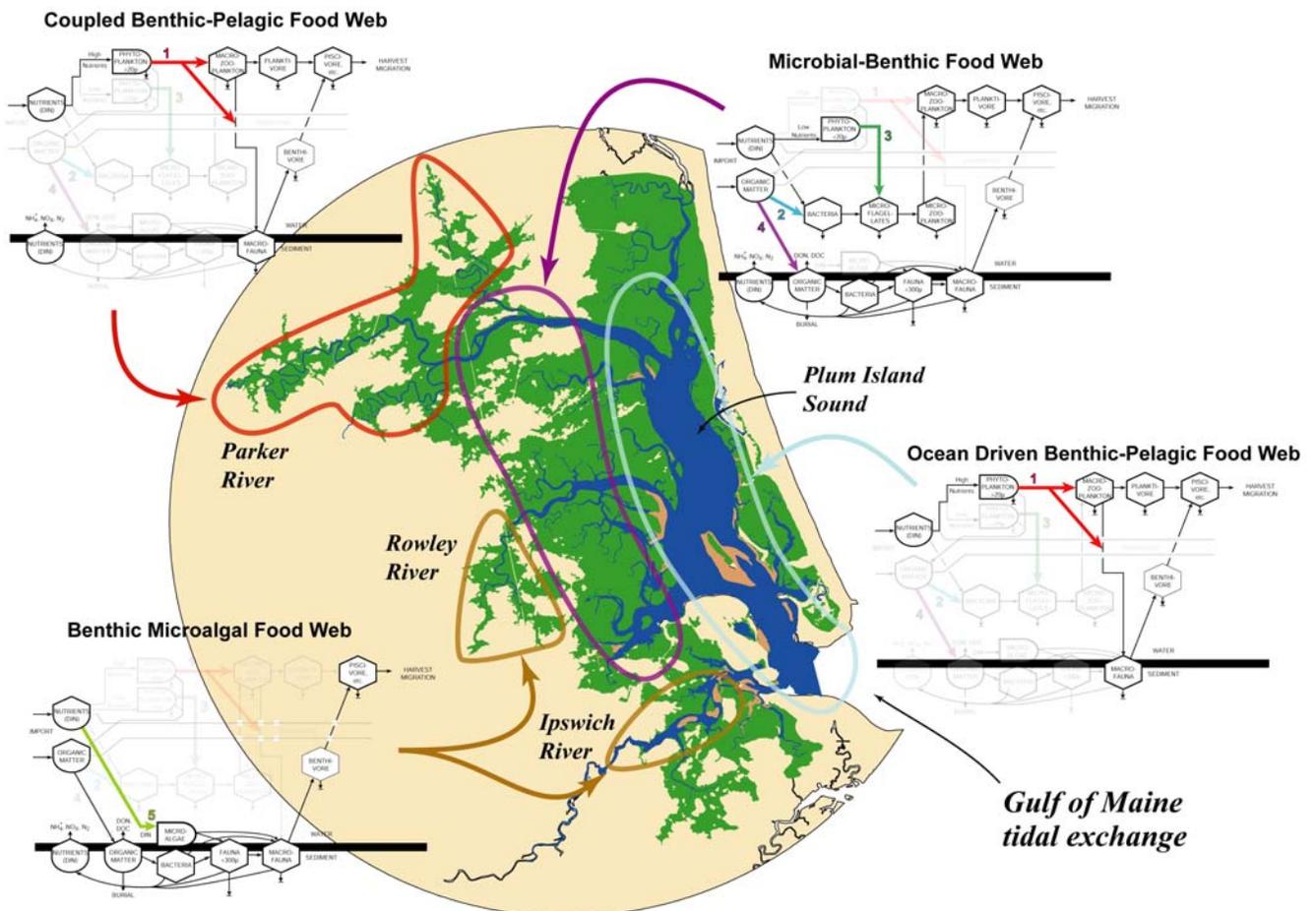


Fig. 8. Spheres of Influence: external drivers, especially H<sub>2</sub>O residence time, define a template whereupon the effects of DIN and OM inputs on foodweb structure operate. Here we show 4 foodweb structures that develop in areas of the estuary that have different hydrodynamic templates and loading combinations.

**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 6).

- 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?**

Integration of the various programmatic areas is the 6<sup>th</sup> programmatic area, and is accomplished through simulation modeling, long-term experiments and a whole system <sup>15</sup>N addition experiment.

**RESEARCH APPROACH AND SCHEDULE - RESEARCH IN EACH OF THE PROGRAM AREAS CONSISTS OF THE FOLLOWING ELEMENTS:**

- Detailed, process-based research focused in specific program areas
- Long and short-term experiments designed to study mechanisms controlling processes
- Long-term field observations to detect trends in drivers and system response
- Comparative ecosystem research to assess generality of our understandings
- Modeling to test hypotheses, to guide research directions and to integrate within programmatic areas.

Over the long-term, we expect to devote roughly equivalent effort into each program area. However, due to person-power and logistical constraints our strategy has been to shift research focus from one program area to another over time.

**Q1-Watersheds:** mostly continuous effort.

**Q2-Marshes:** mostly continuous effort.

**Q3-Water Column:** mostly monitoring since years 2-3.

**Q4-Benthos:** effort focused in yrs 1 and 7.

**Q5-Higher Trophic Levels:** effort focused in yrs 4 and 5.

**Synthesis:** mostly continuous over time but with added focus in yrs 9 and 10

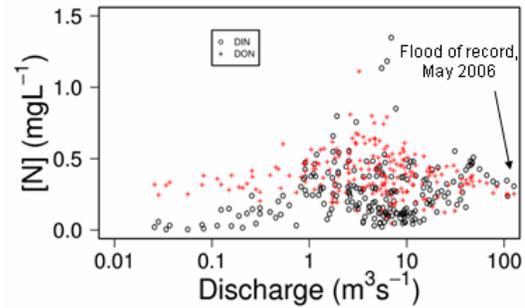
The LTER has enabled us to leverage substantial additional, non-LTER funds (**see Appendices**). These additional funds have enabled us to significantly augment research beyond that proposed for the LTER. For instance, watershed research was augmented through the LINX II project in years 6-8 and will again be beefed up for the next 4 years through an NSF project focused on “scaling” and another on coupled natural-human systems. Marsh research was augmented in yrs 4-7 with EPA funding. Benthic research has been augmented the past 2 years through Sea Grant funding. Research on higher trophic levels (striped bass and river herring) has been augmented through Commonwealth support the past 4 years. Synthetic research was augmented in yrs 6-9 through the TIDES tidal creek fertilization project.

## **Research Report Outline**

In the following sections we report on research progress for each of the program areas plus integration and simulation modeling. Then we provide overviews of information management and technology, LTER network activities, education & outreach, and site management. Several appendices document LTER products, leveraged grants awarded and participants.

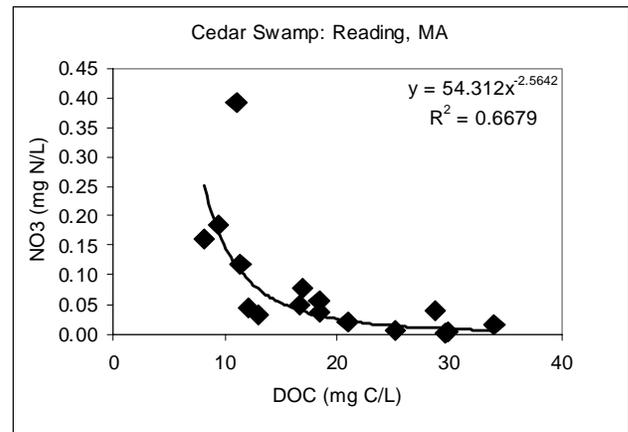
**Q1 – Watersheds: What is the magnitude and long-term pattern of freshwater runoff and organic carbon and nitrogen and inorganic N loading from watersheds to the estuary?**

To address this question, we have used a combination of monitoring, experimental, and modeling approaches. Two specific research questions guide these efforts: **a) How do spatial and temporal factors organize basin-scale outputs to the estuary?** and **b) What are the key controls on water and biogeochemical sources, transformations, and sinks throughout the watershed?** During the past three years we have 1) routinely monitored 5 sites (2 dams, 3 headwater catchments draining representative land uses, including newly established wetland dominated site), 2) conducted tracer and manipulation experiments in headwater streams, 3) further developed and refined river network biogeochemical models. Our approach also incorporates land use change modeling to better understand this driver (Clark U.), as well as fish population/habitat studies (U. Mass), which are influenced by hydrologic and biogeochemical patterns and therefore involve complementary questions involving river network structure. Several new watershed projects are in the beginning stages. These efforts address scaling aquatic processes throughout the basin (funded by NSF-Ecosystems, with Co-I's at MBL, UNH and Penn State), and better understanding the linkages and feedbacks between human activities and natural systems (funded by NSF-Coupled Human Natural Systems, with Co-I's at Clark U., UNH, and MBL).



**Fig 1-1. DIN and DON concentration vs. discharge at the Ipswich basin mouth from grab samples between 1994 and 2006. The highest discharge points were collected during the flood of record, May 2006.**

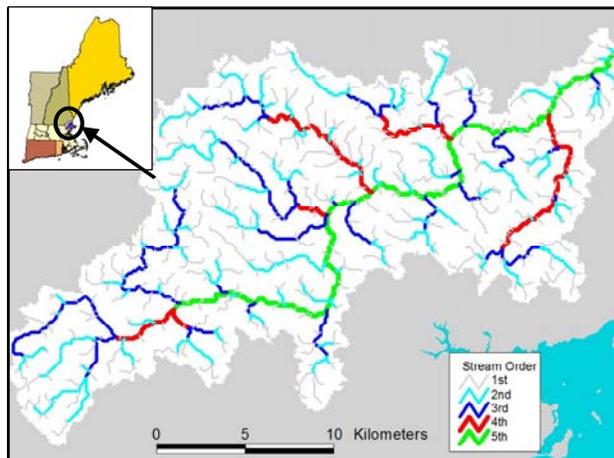
**(i) Monitoring** A number of publications have resulted in the past 3 years from our effort to monitor the hydrologic and biogeochemical changes related to land use change. These papers document a) changes in the hydrological cycle over the past 70 years due to changing climate, water use, and land use (Claessens et al. 2006, Pellerin et al. in press) b) changes in nitrogen retention and nitrogen and solute fluxes related to suburbanization (Williams et al. 2004, Williams et al. 2005, Wollheim et al. 2005), and c) the importance of wetlands as C and N sources in coastal watersheds (Raymond and Hopkinson 2003, Pellerin et al. 2004). Ongoing monitoring builds on this previous effort, and continues to extend our understanding of nutrient biogeochemistry in the watersheds over a range of hydrologic conditions and land uses (e.g. Fig 1-1). Measurements during the flood of record in May 2006 extended our observational record of nutrient export fluxes to the complete range of hydrologic variability. Although we expected significant dilution during this record event, we found that nutrient concentrations are similar to those during other storms with lower peak flows, indicating a



**Fig 1-2. Nitrate concentrations decline with increasing DOC concentrations in a wetland dominated headwater catchment. Based on grab samples collected between 2005 and 2006.**

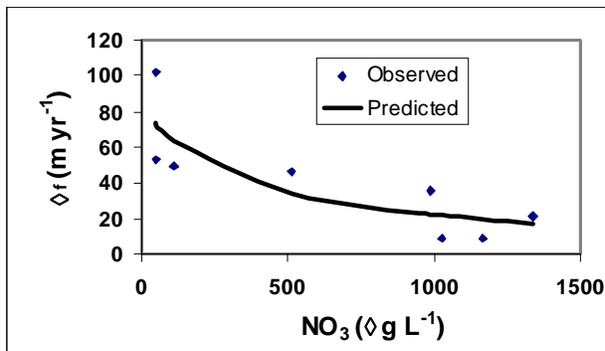
sustained source of N in the watershed (Fig 1-1). Based on previous results demonstrating that nutrient fluxes differ in wetland areas (Raymond and Hopkinson 2003, Pellerin et al. 2004) and the prominence of wetlands in the watersheds (20% of the basin), we began (2005) monitoring a wetland dominated (~ 50%) headwater catchment to better understand the carbon and nitrogen biogeochemistry of this important land cover. Preliminary results suggest wetland catchments have strong seasonal patterns in DOC (winter minima, summer maxima), and a strong negative correlation between NO<sub>3</sub> and DOC (Fig 1-2). This information will be extremely useful for better understanding source and fate of nutrients within the basin and exports to the estuary.

**(ii) Experiments** Since 2003, we have conducted <sup>15</sup>NO<sub>3</sub> tracer as well as short-term manipulation experiments, to better understand N cycle controls in streams and rivers of the basin. As part of the LINX2 experiments, the fate of <sup>15</sup>NO<sub>3</sub>-N was tracked in nine headwaters streams (three each in urban, agricultural, and forested land use). The experiments revealed that denitrification is an important process in these streams, and is not affected by land use in the contributing catchment per se. However, uptake velocities decline with increasing N concentrations, indicating a saturating effect (Fig 1-3). This has important implications regarding how well aquatic systems can respond to increased N inputs related to suburbanization ((Williams et al. 2004, Wollheim et al. 2005), and is being explored with river network modeling (see below). Results from the Plum Island stream experiments are included in a national synthesis paper that is currently under review (Mulholland and others in review). In addition, LTER graduate student Joe Thouin studied the interactions between oxygen, dissolved organic carbon and nitrate dynamics in wetland streams by manipulating both oxygen and DOC in the flowing surface water using stream solute techniques. These experiments suggest that the relationship between DOC and nitrate will require a better understanding of oxygen dynamics in the system (Thouin et al. in preparation).



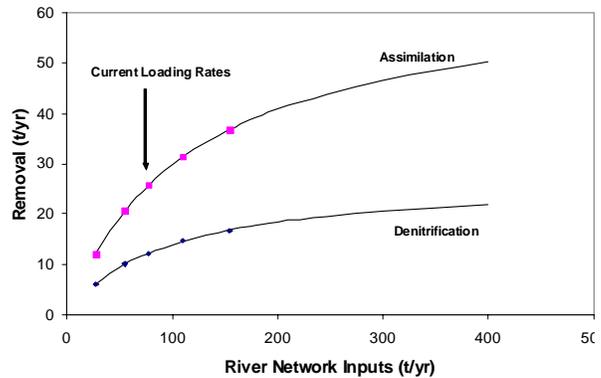
**Fig 1-3. Distribution of stream orders in the gridded river network (120 m resolution) that is used for the Ipswich River network model.**

**(iii) Biogeochemical Modeling** Biogeochemical modeling has focused on river network N removal both from a theoretical (Wollheim et al. 2006) and Plum Island specific perspective (Filoso et al. 2004, Wollheim et al. 2004, Wollheim et al. In Preparation). Additional work has focused on better understanding the role of spatial heterogeneity in determining variability of N in headwater streams (Fedorko et al. 2005). Modeling of land use change, an important driver, is also ongoing and is described below. A theoretical N removal model was used to reconcile different interpretations in the scientific literature of the role of river size and was used to explore how hydrologic, geomorphologic, and biological factors interact to determine the strength and distribution of N removal through river networks (Wollheim et al. 2006). This work set a foundation for modeling N removal in the Ipswich River network. A spatially distributed river network model (Fig 1-3) was developed for the Ipswich to explore the impact of empirical process measurements (from LINX2) at the network scale. This modeling suggests that the river network can remove between 50-70% of DIN inputs from land during baseflow conditions, but much less over annual time scales (14-40%) because most N inputs occur during high flow



**Fig 1-4. Denitrification uptake velocity ( $\text{m yr}^{-1}$ ) declines as nitrate concentrations increase in nine headwater streams from the LINX2 project. Process saturation indicates that N enriched streams have a**

periods when channel process have less influence over nutrient fluxes (Wollheim et al. in preparation). Because of process saturation (Fig1-4), the percent of inputs that can be removed by the river system is predicted to decline (Fig1-5). River network models based on the Ipswich have been extended to the global scale to better understand the role of river systems in the global N cycle (Wollheim et al. in review).



**Fig 1-5. Predicted capacity of the Ipswich River network to impact nutrient export fluxes declines with increasing N input to the river system because of process saturation. The denitrification model scenario is based on rates shown in Figure 3. The assimilation scenario is based on total nitrate uptake from the LINX2 experiments, and assumes that all uptake is ultimately denitrified.**

**(iv) Landuse Change Modeling** Land use change modeling is a critical component of the watershed program, because land use is such an important driver. The results of this work are summarized in several publications (Pontius et al. 2003, Pontius et al. 2004, Pontius et al. 2006). We used the model Geomod to extrapolate forest change over a century for the Plum Island Ecosystems. Geomod uses calibration information between 1971 and 1985 in order to predict the changes from 1985 to 1999, at which point the validation procedure measures the model's predictive accuracy. Then the model is re-calibrated with information from 1985 to 1999 in order to extrapolate into the future, assuming a business as usual scenario. As time progresses, the expected accuracy approaches 0.5, which is the probability at which the model's prediction is as accurate as a random prediction, since the application involves two categories. The extrapolated accuracy of the prediction for the entire study area in the year 2097 is 68 percent. These results will help us predict changing nutrient fluxes into the future, including an assessment of uncertainty.

**(v) Fish Population/Habitat Studies** A new component of the LTER watersheds research effort is the study of river herring populations and habitat, led by Martha Mather at the University of Massachusetts. River herring are an important component of coastal ecosystems because they link freshwater and ocean productivity, but their populations have declined due to human activities that alter the hydrology and biogeochemistry in the river system. To better understand the herring decline and the lack of response to extensive restocking efforts, Mather and students are radiotagging natural and restocked fish and identifying preferred habitats. Herring spent most of their time in the lower river's pool habitat above the first dam (Fig 1-6), and spawn in side pools, which are vulnerable to fragmentation as water levels dropped. Habitat surveys will determine what physical features are important for herring spawning and juvenile survival. Both the fish and biogeochemical research focus on riverbed geomorphology, riparian structure, and hydrologic variability, and are therefore extremely synergistic efforts. We plan to explore

whether hotspots of nutrient processing and fish habitat (i.e., river side ponds and wetlands) are related.

**(vi) New Projects/Future Directions**

We have several additional projects in the watersheds that have been independently funded through NSF. These projects address important questions relevant to the Plum Island system and to the wider research community. The first project, on which we just completed the first field season, explores how N removal processes scale with increasing stream size. This effort expands on the LINX2 research in

headwaters streams by exploring the simultaneous scaling of transient storage zones and nitrogen dynamics with increasing stream size. The scaling project uses conservative solute, gas, and nitrate slug additions along the Ipswich main stem, in conjunction with the N<sub>2</sub>:Ar method to quantify denitrification rates. Our first set of experiments was completed in the summer of 2007, and sample analysis is currently underway. In the future, we also plan to conduct <sup>15</sup>N tracer additions along the main stem to better quantify a variety of N cycle rates. The second project, beginning in January 2008, explores the linkages and feedbacks among land cover (suburbanization), land use (human choices on water use, fertilizer application), hydrology, aquatic nitrogen cycling, and estuarine shellfish production in the suburban Ipswich basin. We will develop a model that links these components to understand nonlinear responses of natural systems to human induced changes, and to explore feedbacks from natural systems back to society that potentially govern human actions and decision making. Integration of human-natural systems is an important research topic in the LTER to which we are poised to contribute.

Regionalization Through a grant funded by NSF and the Consortium of Universities for the Advancement of Hydrological Sciences (CUAHSI), UNH is spearheading a regional synthesis center with the primary goal to: *quantify the widespread alteration of hydrologic systems over local-to-regional domains focusing on the Northeast corridor of the United States over a 500-yr period (1600 to 2100)*. This effort is led by Vörösmarty with Co-PIs L. Band, D. Lettenmaier, and R. Vogel, who will convene a working group to include a broad range of scientists from a number of institutions. This activity dovetails nicely with the LTER Strategic Plan, which is to promote synthesis within the LTER network. Regionalization is one means of promoting synthesis that the New England LTERs have been advocating for the network. The working group will study Regional Watersheds, Hydromorphology, and Continental Processes, for the purpose of carrying-out synthesis activities and serving as a test-bed for ideas on how to optimally execute synthesis. The Northeast corridor is the focus area because it offers a data rich environment bearing a long history of human interaction with ecohydrologic systems. The presence of four LTER sites (HBR, PIE, HFR, and BES) and other intensive research sites embedded within larger watersheds provides a context for spatial scaling and for investigating the 500-year history of hydromorphic evolution of regional watersheds. Three of the LTER sites incorporate integrated studies of historical ecohydrologic, land use, and societal change. Three of the sites (HB, PIE, BES) include intensively instrumented, nested watershed systems, while two

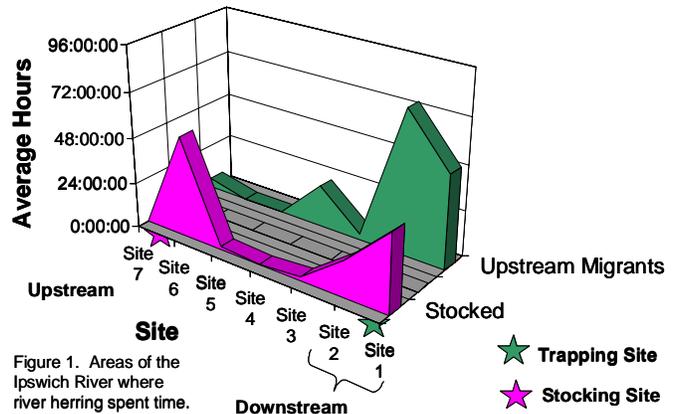


Figure 1. Areas of the Ipswich River where river herring spent time.

**Fig 1-6. Natural and stocked herring prefer the downstream segments of the Ipswich mainstem based on telemetry. Site 1 is the Ipswich Dam, which contains a fish ladder for natural herring runs.**

(HF and BES) include eddy flux towers in forest and urbanized landscapes. All sites incorporate a gradient from forest to urban sites, with comprehensive information and research programs on water, carbon, nutrient cycling. Comprehensive environmental histories of colonization, industrialization, urbanization/suburbanization also help to ensure detection of strong signal-to-noise relationships. Ongoing studies of land-to-coastal ecosystem coupling also argue for the region as an important testbed to assess human impacts on major economically important environments of an entire region.

## Q2-Marshes: How are tidal marsh processes and their connections to estuarine waters regulated by sea level, storms and water and material inputs from land and sea?

To develop a predictive understanding of how terrestrial and oceanic forces affect intertidal marsh systems and how marshes interact with adjacent tidal waters, we examine the processes of primary production, organic matter and sediment storage, and nutrient cycling on marshes throughout the Plum Island Sound estuary. We ask the following two questions: **(2a) how are sediment accretion and primary production in tidal marshes altered by changes in freshwater discharge, material inputs and sea level, and (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?** Significant progress has been made addressing both questions. Long-term primary data sets include measurements of: i) aboveground net primary production (ANPP) on permanent plots dominated by *S. alterniflora*, *S. patens* and *Typha*, ii) pore water chemistry, iii) marsh surface elevation, and iv) breeding bird surveys. These measurements have been supplemented by short term experiments, including a marsh haying experiment, age of organic matter and sediment respiration, marsh drainage, an assessment of the response of ANPP to N and P fertilization and a test of the effect of relative marsh elevation on primary production. Additional descriptive data sets include an extensive survey of marsh elevation by GPS and LIDAR, an analysis of tide pool formation on the marsh surface (Valentine et al. in review), historical aerial photos, and several multispectral images. GPS and LIDAR data was collected with a goal of constructing a digital elevation model that we will couple with tidal and meteorological data to determine the frequency, duration and depth of flooding. The digital elevation model will also be used in conjunction with aerial photos and multispectral data to map the distributions of plant communities. Coupled biogeochemical, geomorphological and hydrological models of the marsh and aquatic subsystems will be used to calculate import-export budgets of nutrients and sediments and to forecast the responses of the marshes to changes in sea level.

**Intersite Research:** We are conducting comparative studies at North Inlet, SC where there are strong contrasts in physical drivers such as climate and tidal range. The primary data sets being developed under **Q2a** are being duplicated at North Inlet, SC where we have 23 years of data on marsh primary production. Specifically, we are addressing the following questions: 1) How do the temporal patterns in annual primary production correlate in salt marshes from different regions? 2) How do peat-dominated NE and mineral-dominated SE salt marshes differ in terms of sediment accretion, nutrients, and decomposition? 3) How different are the controls on primary production?

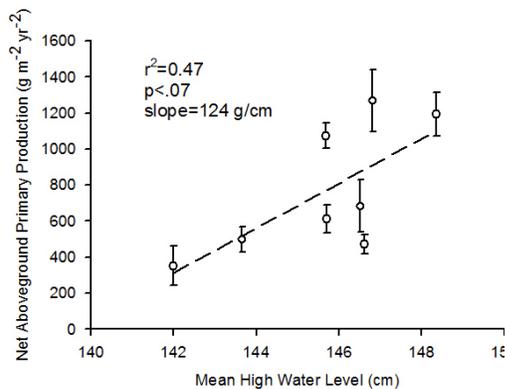


Fig 2-1 ANPP of *S. alterniflora* at PIE as a function of mean high water level.

**Research Results Highlights: Primary Production**— Current evidence supports our original hypothesis that annual primary production in Plum Island salt marshes is variable and sensitive to changes in mean sea level. ANPP varies annually by a factor of 3 and increases when mean high water level is higher (Fig 2-1). Provided the marsh surface is higher than the optimum elevation, productivity will rise as flood frequency increases. Mean high water level, a proxy for flood frequency, changes as

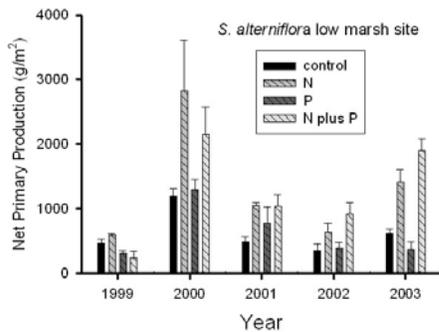


Fig 2-2. Annual ANPP of *S. alterniflora* from sites fertilized with combinations of N and/or P and controls.

a consequence of seasonal and interannual variability in mean sea level and tidal amplitude. Flood frequency can modify a number of biogeochemical parameters of consequence to the plant community, including pore water salinity.

A nitrogen-phosphorus factorial fertilization study has documented that *S. alterniflora* marshes at PIE are N-limited, but not P-limited (Fig 2-2). The positive response to nitrogen has also been observed following a fertilization of tidal creeks (Deegan et al. 2007, Drake et al. 2007). The insensitivity to P at PIE differs from experiments in North Inlet, SC where there is a strong secondary response of NPP to P-fertilization. The lack

of a response to P at PIE suggests that the marshes here could be co-limited by Fe. Indeed, concentrations of  $Fe^{+2}$  in pore water are higher at North Inlet, and  $S^{-2}$  concentrations lower. These differences are probably due ultimately to the relative higher abundance of mineral sediment at North Inlet.

ANPP at PIE and North Inlet, SC are equivalent. Both show a high degree of interannual variability that correlates with changes in MHW, but sensitivity to MHW appears to be higher at PIE. Theoretically, sensitivity to MHW is a function of the relative elevation of the marsh surface and tidal amplitude. Relative to North Inlet, PIE has a higher tidal amplitude and its marshes are situated higher in the tidal frame.

Results of a marsh haying experiment (haying is a traditional activity on the PIE salt marshes since colonial times) show that this practice favors *Spartina patens* at the expense of *S. alterniflora*. Furthermore, haying increases plant stem density, decreases standing biomass, stimulates N fixation and sulfate reduction, and has short-term impacts on the marsh invertebrate community and benthic algae (Buchsbaum et al., in review).

**Marsh Pore Water Chemistry**—Surface salinity (10 cm) averages 5 o/oo lower in the *S. patens* high marsh site (20.6 o/oo) compared to the *S. alterniflora* low marsh site, but the variability is greater at the high marsh site. Salinity at the high marsh site has been as great as 49.5 and as low as 8.4 o/oo. In contrast, the range in the low marsh has been 47.3 to 14.5 o/oo. Salinity at the *Typha* site has been as great as 10.9 o/oo, but is more typically 3 o/oo or less.

There are large differences among marsh sites in pore water nutrient and sulfide concentrations. While sulfide concentrations at depth are greater in the high marsh dominated by *S. patens*, at the surface (10 cm) they average 35 and 130  $\mu\text{mol/l}$  in the high and low marsh, respectively (Fig 2-3). The surface 10 or 20 cm of sediment has greater relevance to the plant community.

The chemical behavior of the marshes at PIE does not fit a popular heuristic model that portrays the high marsh as a low stress habitat in which *S. alterniflora* enjoys a competitive advantage in high nutrient environments (Levine et al. 1998). Concentrations of

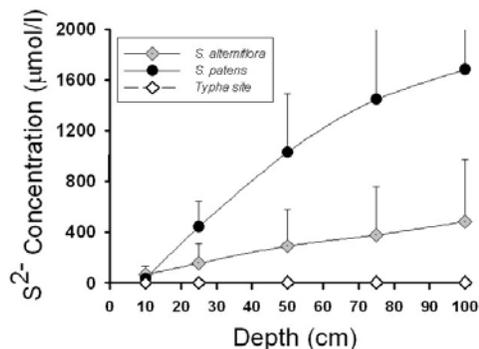


Fig 2-3. Time-averaged depth profiles of pore water sulfide concentration by site.

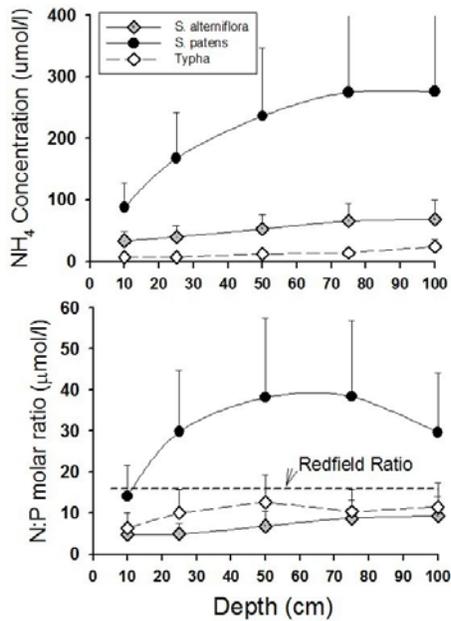


Fig 2-4 Depth profiles of time-averaged, geometric mean (+ 95% CI) pore water  $\text{NH}_4$  concentrations and the molar N:P ratios of Plum Island marshes.

$\text{NH}_4$  are significantly greater in the *S. patens* high marsh than in the *S. alterniflora* zone (Fig 2-4) at all depths sampled. N:P ratios are also greater in the *S. patens* zone and at depths greater than 10 cm exceed the Redfield ratio (Fig 2-4). The elevated levels of  $\text{NH}_4$  in the high marsh suggest that this habitat may actually subsidize the low marsh plant community with nitrogen. The  $\text{NH}_4$  concentration in marsh pore water exceeds the sum of total dissolved and particulate nitrogen in surface water at the Parker R. dam by an order of magnitude, which indicates that N-fixation in the marsh is an important process or the marsh efficiently traps and sequesters particulate nitrogen.

*Marsh-Estuary Linkage*—Ground water level recorders installed in *S. alterniflora* and *Typha* marshes are used to monitor the dynamic response of subsurface water in relation to tidal and climatic forcing. Data on sediment structure, hydraulic conductivity, porosity and specific yield are providing estimates of the quantity of water, DOC and nutrients draining from the marsh to the tidal creeks. Estimates of these fluxes are being compared

with measures of estuarine metabolism conducted under the Water Column Programmatic Area (Q3). Gardner (in review) has estimated that the annual seepage from marshes into tidal creeks averages  $211 \text{ m}^3 \text{ yr}^{-1}$  per meter of creek length. Extrapolating these rates to the entire estuary, using LIDAR imagery to compute the length of marsh edge (1900 km), gives a total seepage rate of  $401 \times 10^6 \text{ m}^3/\text{yr}$ . This is greater than the freshwater discharge into the entire PIE estuary ( $347 \times 10^6 \text{ m}^3/\text{yr}$ , Vallino and Hopkinson 1998) and, in light of the high nutrient concentrations in pore water (Fig 2-4), suggests that the marsh has a significant effect on the water column, not as a sink for dissolved carbon and nutrients, but as a source.

*Sediment Accretion*—SET platforms and feldspar marker horizons are monitored at 12 sites across 3 major marsh types in order to measure sediment accretion and changes in marsh surface elevation. In addition, we have advanced a theoretical model that describes the feedbacks among marsh vegetation, sedimentation and sea level (Morris et al. 2002). Briefly, stable marshes are situated high in the tidal frame, higher than the elevation that is optimal for growth. When the relative elevation of the marsh decreases (due to rising sea level or compaction), primary production is stimulated, biomass density, drag, and sedimentation rate increase, which raises the elevation of the marsh surface. The equilibrium elevation is a function of the rate of sea level rise, sediment availability, and other factors. The implications of this process to competitive relationships among plant species (Morris 2006) and for ecological engineering solutions (Morris 2007a) also have been described. The model has recently been modified to explicitly treat belowground organic matter production and its dependence on relative elevation (Morris 2007b). The results indicate that the root:shoot ratio increases with increasing elevation of the marsh surface, which may explain the formation of peat marshes in regions where isostatic rebound has lifted coastal marshes at rates approximately equal to the eustatic sea level rise. This is depicted conceptually above (Fig 2-5). At the lowest rates of sea-level rise, marshes will equilibrate at a relatively high elevation (Fig 2-5 left) where the opportunity for mineral input is limited,

aboveground production is reduced, and belowground production is maximized. These circumstances lead to peat formation. At faster rates of sea-level rise, marshes equilibrate lower in the tidal frame where aboveground production and mineral inputs are greater and belowground organic matter production reduced (Fig 2-5 right). We hypothesize that this, and differences in mineral sediment availability, are the fundamental differences between peat-forming New England marshes and mineral-rich southeastern marshes.

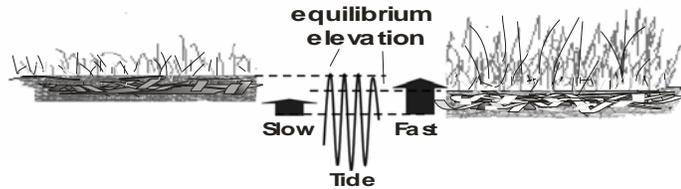


Fig 2-5. Conceptual model of the alternative responses of marshes to rate of sea-level rise.

### **Q3 – Water Column: How does planktonic community structure and production respond to changes in organic matter, nutrients, and water fluxes?**

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. Our research addresses three specific research questions: **3a) What algae and protozoan species are present in the plankton and what is the size distribution of algal productivity?** **3b) What are the interactions between bacteria, their species and metabolism, and different chemical conditions in the estuary?** and **3c) What is the metabolic response of the planktonic system to natural variations in nutrients and organic matter?**

We have used the approach of sampling along the estuarine transect from rivers to the ocean to examine the chemical and biological structures and processes within the estuary. This approach takes advantage of the natural experiments produced by variability in location and magnitude of inputs of freshwater, nutrients and organic matter from rivers, the sea and marshes. Much of this variability is produced by seasonal shifts in freshwater inputs and the hydrodynamics of the estuary. In the Parker River and Plum Island Sound, water residence times are short (< 5 days) during the late winter and spring seasons and populations of large-celled phytoplankton do not have time to develop within the estuary. Crump et al. (2004) estimated residence times of 3-5 days in the spring and 8 days in the summer and fall. During late winter and spring phytoplankton cells are transported by the tides from the coastal ocean into the Sound. During the June to September period of low river discharge large-celled phytoplankton blooms occur regularly in the upper Parker River when residence times are >7 days. Transect collections are made from one to three or more times per year for nutrients, phytoplankton, primary productivity, respiration and zooplankton. Timing of transects is often chosen to capture the contrasts between the winter-spring high flow and summer-fall low flow conditions in the estuary.

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

Dr. David Patterson of the MBL has compiled photos of the common planktonic organisms of the Plum Island Sound estuary. This is a start on the goal of compiling a photographic, web-based catalog of algal species (<http://starcentral.mbl.edu/microscope/portal.php?pagetitle=collectiondetails&collectionID=11&themeid=0>) present in the plankton against which to measure species change over the next decades.

We have initiated a second approach for monitoring the variation in the major classes of phytoplankton in the estuary. The CHEMTAX method involves using HPLC to quantify the algal pigments present in a sample of estuarine water. The different pigments are used as indicators of the presence and abundance of diverse taxonomic groups of phytoplankton. In Plum Island Sound we can identify diatoms, chlorophytes, cryptophytes, dinoflagellates, and cyanophytes. We have been performing spring and fall CHEMTAX transects since 2002 and during 2006 we sampled seven times during the April to December period (Fig 3-1). Diatoms consistently dominate the phytoplankton assemblages throughout the estuary followed by chlorophytes with cyanobacteria least abundant. The CHEMTAX analysis can be improved by using detailed taxonomic information from selected samples to optimize the algorithms used to convert the pigment ratios to chlorophyll units for each class. This remains to be done.

Samples for phytoplankton counts preserved in Lugol's solution and for zooplankton preserved in alcohol are taken for the archives during each transect sampling.

**Specific Research Question: 3b)**

*What are the interactions between bacteria, their species and metabolism, and different chemical conditions in the estuary?*

DGGE analysis of bacterioplankton communities along the salinity gradient of the estuary demonstrated mixing of freshwater and coastal marine bacterioplankton, and linked the development of a native estuarine community to extended estuarine water residence time during summer (Crump et al. 2004). Extensive analysis of PCR-amplified bacterial 16S rRNA genes from the marine end of the estuary estimated a taxonomic diversity of at least 1,633 ribotypes, and identified high levels of microdiversity by showing that most ribotypes could be grouped into clusters with <1% sequence divergence (Acinas et al. 2004). Thompson et al. (2005) showed a seasonal cycle in the abundance and diversity of organisms within one cluster related to *Vibrio splendidus*, and identified at least 1,000 distinct genotypes each existing at very low concentrations of less than one cell per ml.

In salt-marsh soils, one large-scale study of PCR-amplified 16S rRNA genes from *Deltaproteobacteria*, a sub-phylum of bacteria dominated by sulfur-reducing organisms, estimated a high taxonomic diversity of 623 ribotypes, but found that much of this diversity was microdiversity (i.e., < 1% sequence divergence, Klepac-Ceraj et al. 2004). Analysis of PCR-amplified dissimilatory sulfite reductase (*dsrAB*) genes confirmed these findings and suggested these that sulfate reducing communities are dominated by organisms with high substrate versatility that are capable of completely oxidizing organic matter (Bahr et al. 2005).

Studies of sediment bacteria in Plum Island Sound showed a reduction in diversity of ammonia-oxidizing (i.e., nitrifying) bacteria with increasing salinity (Bernhard et al. 2005) and showed that abundance and community composition of ammonia oxidizing bacteria varied with the rate and kinetics of ammonia oxidation (Bernhard et al. 2007).

While the DGGE method is believed to give a good picture of the bacterial community, very recently another sequencing method called pyrosequencing or tag sequencing has become available at the MBL. NSF has funded Linda Amaral Zettler ( MBL) to sample some 15 aquatic systems at LTER sites including Plum Island Sound. In this method short pieces of PCR-amplified 16S rDNA are attached to small beads, one piece to a bead and each bead is placed in a 35 um diameter hole in a plate. Sequencing takes place as complementary strands of DNA are built up through the sequential addition of nitrogenous bases (plus a sugar and phosphate). The advantages are that tens of thousands of the DNA pieces are sequenced at one time and that very rare pieces are sequenced and identified as well as the most abundant pieces. This new

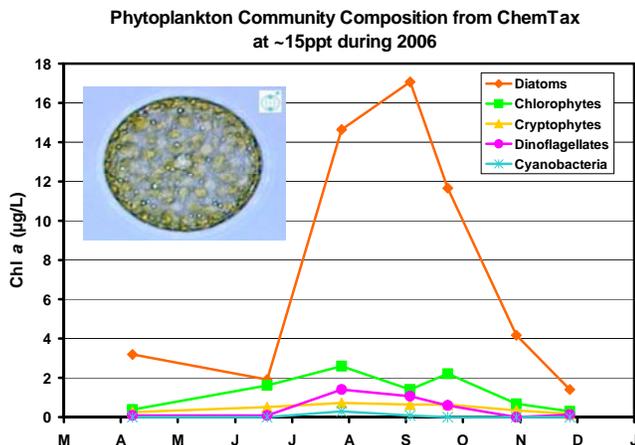


Fig 3-1. The variations in phytoplankton community composition at mid-estuary salinities during 2006. Inset is a photograph of *Actinocyclus*, a common centric diatom in the upper estuary during summer.

technique will give a much more complete picture of the rare forms of bacteria in the community.

The next step in studying bacteria in nature is to determine which of the many kinds of bacteria present are actually active and what processes they are carrying out. One new technique uses the measurement of mRNA (messenger RNA) that is present when a microbe is actively producing the enzymes to carry out a process. This technique is in its infancy but is needed to make the linkage between bacterial processes and the species of bacteria we find in Plum Island Sound and adjacent waters.

**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 nutrient concentrations from season-to-season and site-to-site. These variations in inputs and in-situ processes lead to changes in algal and bacterial productivity. Analyses of these changes in chemistry and populations can produce insights about the response of the planktonic community. We measure metabolism using in-situ diurnal changes in dissolved oxygen concentration (corrected for exchange with the atmosphere) measured at dawn and dusk along the estuarine river to ocean transect. Thus we can calculate the spatial distribution of P, R and NEP along the estuarine transect and calculate by mass balance the potential importance of allochthonous inputs along the estuary. Combined with other analyses, calculations of NEP can provide insight into sources of material sustaining system metabolism. In the Plum Island Sound estuary, there are inputs from rivers and the coastal ocean but also large additional inputs to estuarine waters from the extensive fringing intertidal marshes.

We see strong seasonal and spatial patterns in P and R. Seasonal patterns are amplified in the upper tidal river relative to the Sound (Fig 3-2). The strong seasonality in the upper estuary is attributed to the high seasonal variation in temperature and water residence time. Combining all regions, P averages  $119 \text{ mmol C m}^{-2}\text{d}^{-1}$  while R averages  $217 \text{ mmol C m}^{-2}\text{d}^{-1}$  or nearly twice P. Overall the estuary is markedly heterotrophic ( $-94 \text{ mmol C m}^{-2}\text{d}^{-1}$ ) with the degree of heterotrophy driven by temperature, water residence time, extent of marsh flooding, and watershed C loading.

Estimates of metabolism were calculated for four segments of the estuary. The mid to lower tidal river portion of the estuary is most heterotrophic, presumably reflecting the high ratio of intertidal marsh to open water in that region (Fig 3-3).

We have combined results of watershed organic matter bioassay studies with estimates of loading and water transit times to estimate the relative importance of POC and DOC inputs from the watershed in supporting net heterotrophy. We find that watershed inputs can sustain net heterotrophic demands in the small upper segment but these inputs can sustain only 1 to 40% of demand for the remainder of the estuary. The remaining heterotrophy is probably sustained via inputs of organic matter from marshes, a concept finding support from the carbon isotopic composition of

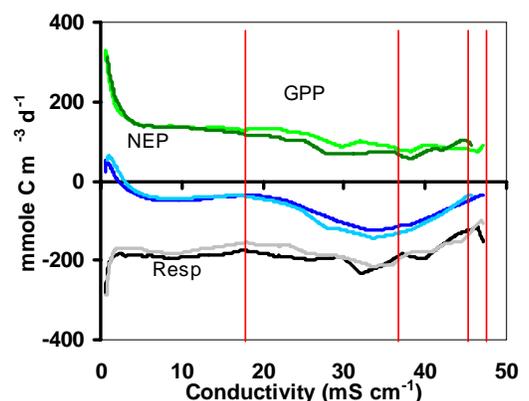


Fig 3-2. The distribution of GPP, NEP and respiration along the estuarine transect based on dawn and dusk dissolved oxygen concentrations corrected for atmospheric exchange.

dissolved organic carbon and estuarine bacteria (Coffin et al. 1989, Peterson et al. 1994, Raymond and Hopkins 2003).

By combining estimates of NEP with measures of marsh grass production, we estimate that 1-45% of above ground macrophyte production is required to fuel the NEP deficit (Fig 3-4).

While the importance of this marsh subsidy is clear, the mechanisms supporting these patterns are not. Large quantities of marsh derived organic matter are exported from the marsh surface and from tidal creek drainage (see Marsh Program Area results). Our indirect estimates of marsh DOC inputs from marsh drainage are substantially higher than most estimates of marsh surface export, but the latter mechanism helps explain lunar cycles in microbial production (Coffin and Wright, unpublished ms, Wright et al. 1987). Additional sites of respiration include the marsh itself with tidal waters capturing this signal through the release of marsh respiratory products during immersion. Better understanding of the coupling between marshes and tidal waters is an area of research we plan to focus on in the next two years of PIE LTER II.

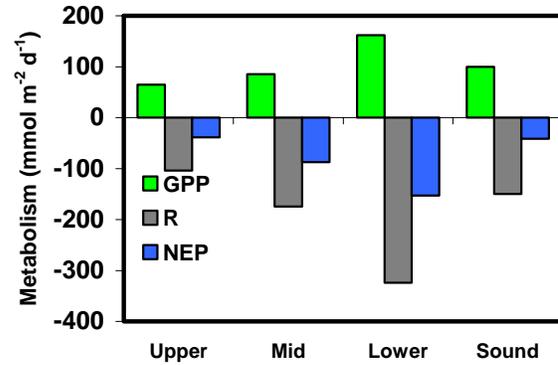


Fig 3-3. Metabolism summary for 3 segments of the riverine portion of the estuary and for the Plum Island Sound. Note the large degree of heterotrophy in the middle segments of the transect.

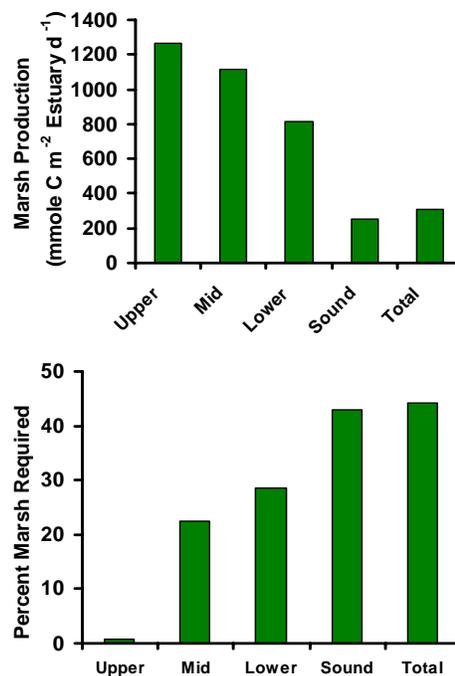


Fig 3-4. Estimates of fringing marsh production per unit area of the adjacent estuarine open water (top) and the percentage of that production required to match the net heterotrophy in the water mass computed from in-situ metabolism measurements.

**Q4-Benthos: How do benthic recycling of nutrients and processing of organic matter respond to changes in freshwater runoff and the quality and quantity of organic matter inputs?**

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, the benthos plays a key role in the processing of low quality organic matter, such as terrestrial and marsh detritus. 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. We ask the following three questions: **4a) How do variations in the salinity distribution in the estuary determine the magnitude and timing of the nutrient release from the water column?**, **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?** and **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?** Each of our three sub-questions is currently being addressed through our monitoring program, as well as by specific process studies and modeling. Our core long-term monitoring measurements include benthic fluxes of oxygen, CO<sub>2</sub> and nutrients at several stations in the estuary. We have been focusing efforts on several stations in the upper and mid-estuary that experience seasonal and inter-annual changes in the salinity of the overlying water and which receive organic matter from a variety of sources including terrestrial, marsh, and plankton. We are also examining annual variability in the C/N ratio in the sediments and in the C/N ratio of what is mineralized. To examine how higher trophic levels respond to variations in organic matter sources, we are examining annual variations in the stable C and N isotopes of consumers including the bivalves *Mya* and *Geukensia*, to see if there are annual variations that relate to changes in discharge and sea level. Benthic fluxes, sediment data and isotope data collected each year are archived in the PIE data base (Ben-PR-FLUX.htm, Ben-PR-Sediment.htm, HTL-PR-Isotopes.htm) on the web site.

**Q4a.** *How do variations in the salinity distribution in the estuary determine the magnitude and timing of the nutrient release from the water column?*

As a result of our monitoring program, we have found strong links between nutrient release and salinity in the upper estuary. Both the seasonal and the inter-annual pattern of ammonium release at this upper estuary site are correlated with salinity and the correlation is much higher than with either temperature or benthic respiration. The mechanisms by which salinity might control ammonium release have been investigated through process measurements, modeling and molecular techniques. First, salinity directly affects ammonium release through ion exchange. We measured exchange coefficients throughout the estuary and found that at low salinities, more than 90% of the sediment ammonium pool is bound to exchange sites on particles (Weston et al. submitted). As a consequence, over the spring, as metabolism increases, ammonium builds up on exchange sites. In summer, as salinity increases, this “trapped” ammonium is desorbed from particles and released into the porewater where it diffuses to the overlying water (Weston et al. submitted). Second, salinity has a large effect on rates of microbial processes including, nitrification, denitrification, and dissimilatory nitrate reduction to ammonium (DNRA) (Giblin et al. submitted; Bernhard et al. 2005; 2007). During summer and early fall, when salinity is high, nitrification rates decrease by nearly an order of magnitude compared to values measured in April. Lower nitrification rates decrease rates of coupled nitrification/denitrification so that N losses as N<sub>2</sub> gas decrease over the summer, even though overall rates of sediment metabolism are

greater (Fig 4-1). This means that in summer a greater percentage of the mineralized ammonium reaches the overlying water. At the same time the preferred pathway for nitrate reduction shifts from denitrification (where the endproduct is N<sub>2</sub>) to DNRA where the end product is ammonium (Fig 4-1). This shift in pathways further favors summer and early fall ammonium releases.

The release of ammonium from the sediments in summer has important biological consequences. In mid-summer, discharge is at its lowest levels and N inputs from the watershed are negligible, but residence time in the estuary is high. This is the period of time where we often observe large mid- late-summer phytoplankton blooms. We believe that the release of nitrogen from the sediments is an important factor contributing to these mid and late summer blooms.

Inter-annual variations in salinity are sometimes sufficient to change the seasonal pattern of N cycling. For example in 2004, there was sufficient discharge during the entire summer to maintain low salinities in the upper estuary and denitrification rates stayed high. In 2005, mid-summer salinities were again high and we returned to the more typical pattern of very low denitrification rates during summer (Fig 4-2).

At the mid-estuary site, we see a very different pattern. Here salinity changes are more modest and do not exert a strong control on N cycling. Denitrification rates do not show the late summer depression that we observe in the upper estuary sites and we do not see a strong relationship between salinity and N release. In contrast to our upper estuarine site, ammonium release is well correlated with benthic respiration.

We have examined a key microbial group, ammonium oxidizing bacteria (AOB), to see how community size and composition changes with salinity. Community composition was assessed using terminal restriction fragment length polymorphism (TRFLP) analysis of the ammonium monooxygenase (*amoA*) gene. We found that the community in the lower, more saline estuary was less diverse than in the upper estuary and that the community does not appear to shift over the course of the season as salinity in the estuary changes (Bernhard et al. 2005). The community composition was relatively stable over all three years of study. To better determine how AOB abundance controls nitrification rates, we estimated AOB abundance by measuring gene copies

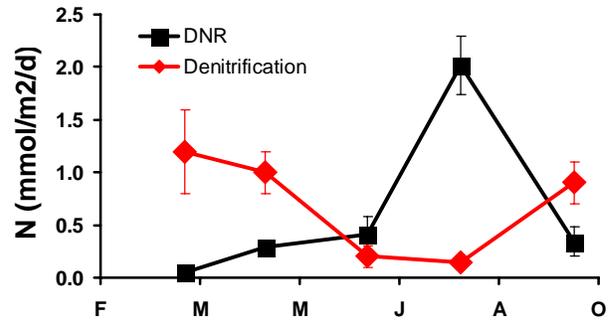


Fig 4-1. Rates of denitrification and DNRA at an upper estuary site. DNRA data is from 1999 only; denitrification data is composite from several years.

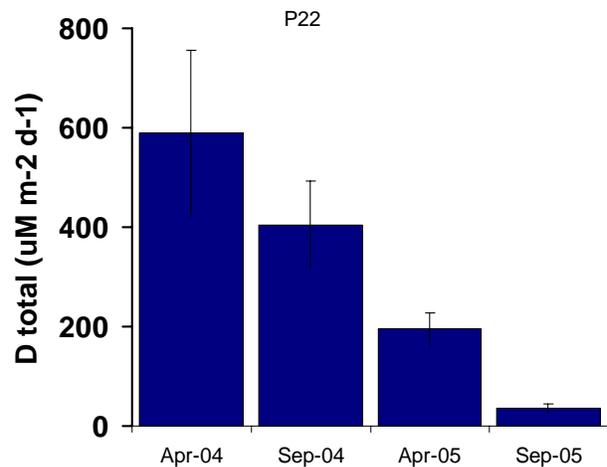


Fig 4-2. Denitrification rates at our upper estuary sites. During 2004 salinity was low in the estuary for most of the summer and rates during both April and Sept. ambient low tide salinities were zero. In 2005 Salinities in April were near zero but were 10 psu during the September measurements.

(*amoA*) using real-time PCR and measured potential nitrification rates on subsamples taken at the same time. Both AOB abundance and potential rates were significantly higher in spring than late summer (Bernhard et al. 2007). Correlations between rates and abundance varied significantly among sites, but showed site-specific ammonia oxidation kinetics related to AOB community structure (Fig 4-3). This suggests that either the rate of nitrification per copy of the *amoA* gene varies among populations or that we did not fully quantify all of the potential nitrifiers. Nitrifying archaea were identified by Bernhard and colleagues in our samples (Konneke et al. 2005) and these would not have been detected with the primers used.

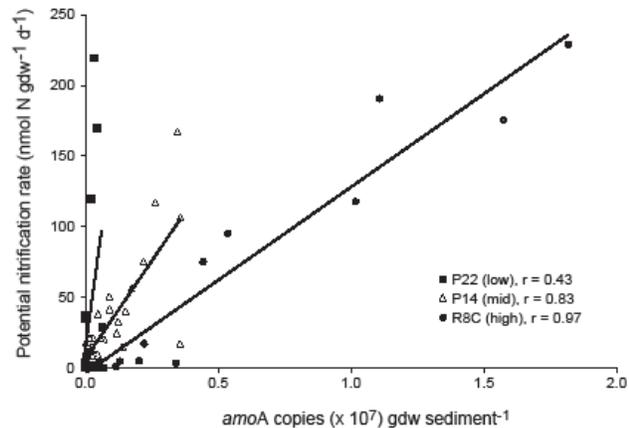


Fig 4-3. Correlation between potential nitrification rates and *amoA* gene copy number at sites in the Plum Island Sound estuary, representing low, mid and high salinity.

The effect of salinity on potential nitrification rates was evaluated by incubating sediment from each site under four salinity conditions (0, 5, 10 and 30 psu). At all sites, rates were generally highest in the intermediate salinity treatments, but rates at the upstream site were inhibited at high salinity, while rates at the two downstream sites were inhibited at the lowest salinity. Therefore, although salinity appears to be an important factor in determining AOB distribution, it may not be the only factor as AOB exhibited a broad range of salinity tolerance in our experiments. Our results indicate that there are significant differences in abundance and community composition of AOB along the salinity gradient, and the differences are reflected in community function.

Finally we have examined how salinity may affect the N cycling pathways in both subtidal and inter-tidal sediments. Ketil Koop-Jakobsen, a Ph.D. student, has been examining the importance of anammox (anaerobic ammonium oxidation) and DNRA in different regions of the estuary. He has found that anammox is of minor importance in PIE marshes, contributing less than 7% of the total  $N_2$  flux in all of the major vegetation types regardless of salinity. DNRA is more significant, especially in summer, and can be an important nitrate sink, and the link between DNRA and salinity is currently being investigated.

**Q4b** *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?*

We have experienced large inter-annual changes in discharge over the study. We expected that changes in watershed inputs, and inter-annual differences in the upper estuary phytoplankton blooms would drive rather large inter-annual changes in benthic metabolism and nutrient fluxes. To date we have not found any direct correlations between discharge or salinity and benthic respiration. Instead, we have found benthic respiration at our upper estuary site is well correlated with water temperature, which explains over 60% of the variability and nutrient dynamics are controlled by salinity as detailed above. Sediment C/N shows significant seasonal and inter-annual variability, perhaps reflecting the mix of organic matter sources. But C/N does not correlate well with benthic respiration. In contrast, at the lower estuary site, benthic

respiration was not strongly related to temperature, and year-to-year variation appears to be related to the size of the infaunal clam population. Because a great deal of organic matter processing at this site is mediated directly by the infauna, we see good correlations between sediment metabolism and nutrient release. We make the benthic flux measurements at the same time as there are whole system metabolism measurements and we are currently examining how the contribution of benthic metabolism to total system metabolism changes over the seasons and between years.

The picture that has emerged from both 4Qa and 4Qb is that our upper and mid-estuarine sites behave quite differently – in the upper estuary extreme salinity variations function as both a physicochemical and a physiological control on N cycling. In contrast, variability at the mid-estuarine sites is driven in large part by animal abundance, which is controlled by many factors including harvest by humans. This difference in controls represents a modeling challenge. To date we have concentrated on modeling the N dynamics in the upper estuary where we have successfully been able to model the effect of salinity on N cycling (Weston et al. submitted). This data has been used to project the effect that changes in hydrology would have on N release in the estuary (Fig 4-4).

**Q4c** - 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?

We are compiling long-term data on the isotopic composition of consumers in the benthos to see how organic matter sources may change under different hydrologic regimes. We have found that the carbon isotopic composition of sediments, and both the ribbed mussel (*Geukensia*) and the soft shell clam (*Mya*) shows fairly low inter-annual variation. The nitrogen isotopic composition shows more inter-annual variation, especially in the mid-estuary. However, at the same time, the sources (i.e. POM, benthic algae) also show more temporal variation. Overall the isotopes show much more variation spatially down estuary, than they do temporally, suggesting that while isotopes can help us elucidate the importance of different organic matter sources within the estuary, they may not be sensitive to detect small differences in the availability of different sources between years.

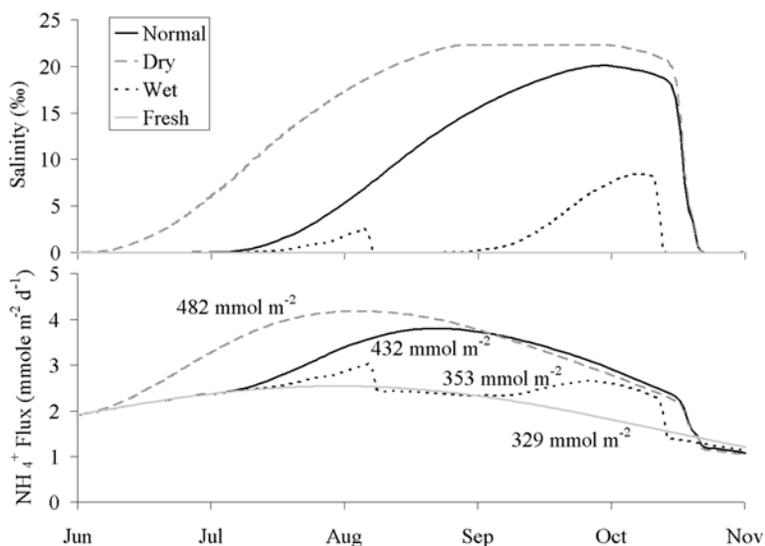


Fig 4-4. Results from 4 nitrogen exchange model runs where the seasonal salinities were varied to simulate normal, dry, wet and fresh water years (*top graph*) and the resulting NH<sub>4</sub><sup>+</sup> flux (*bottom graph*). The total flux of NH<sub>4</sub><sup>+</sup> from the sediments for the 5-month period is indicated.

**Future Directions:** Our previous research suggests that both denitrification and DNRA are extremely important in the upper estuary while anammox is less important. However, we need to confirm that this is the case throughout the estuary. A major focus will be to investigate how tidal, seasonal, and inter-annual changes in salinity affect the partitioning between the processes that remove nitrogen as gaseous N (denitrification and, anammox) vs. those that conserve

nitrogen in the ecosystem (DNRA) in other locations in the estuary. We also believe that nitrate availability will alter the partitioning between denitrification, anammox and DNRA so we intend to measure these processes at a number of locations that vary in nitrate inputs and also take advantage of an ongoing N fertilization study at Plum Island to expand on the range of sites we can measure. Finally we intend to expand our simulation model in the upper estuary by adding in DNRA and anammox.

**Q 5 – Higher Trophic Levels: How do the structure and function of higher trophic levels respond to changes in land, atmospheric and oceanic forcing as well as fisheries harvest?**

Our overall goal is to understand how higher trophic levels, such as fish, invertebrates and birds function in estuarine systems. 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 work is examining three key questions: **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? 5b) How do higher trophic levels regulate trophic structure and the flow of energy and nutrients? 5c) How does the spatial configuration of habitats influence the production and function of higher trophic levels?**

During the last three years we have made progress by (i) isotopic measurements of key functional groups to examine annual variability in organic matter support, (ii) determining growth and isotopic composition of a key fish, the mummichog (*Fundulus heteroclitus*) across the estuarine landscape from brackish to marine, (iii) conducting experiments that alter primary production and trophic structure in salt marsh systems, (iv) tagging of striped bass to determine if they exhibit site and habitat fidelity and if there are 'hot spots' for bass foraging, and (v) developed new models of animal movements to understand the importance of environmental variability in determining habitat use by fish. In support of these questions, we have received supplemental funding from NSF Integrated Challenges in Environmental Biology, the MA Division of Marine Fisheries and a variety of sport fishing groups through our Adopt-A-bass and Adopt-a-herring outreach programs.

(i) We have used natural isotope measurements to assess the influence of different organic matter sources and the food web variability of fresh, mesohaline, and marine dominated areas of the estuary. For the past 8 years we have conducted an annual isotopic survey of 10 functional groups at three locations in the late summer (Figs 5-1, 2, 3). This information has confirmed that the signatures of organic matter utilization in fresh riverine, mesohaline salt marsh dominated, and marine regions identified by Deegan and Garritt (1997) are persistent features of the Plum Island Sound Estuary (Fig 5-1). Organisms found in the upper freshwater region have carbon isotopic values that are much more negative than those in

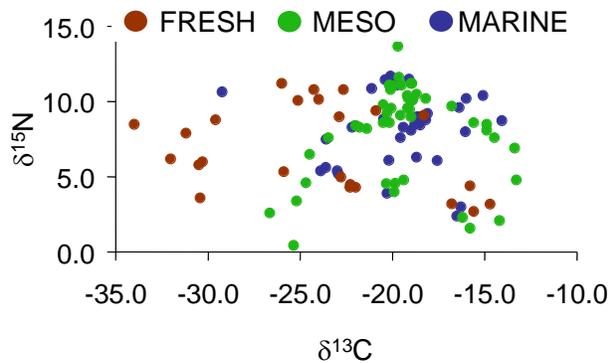


Fig 5-1. Cross plot of C and N isotopes for all 10 functional groups collected over the past 8 yrs at fresh, mesohaline and marine locations. Collections confirm the persistent nature of fresh riverine, meso, and marine food web regions.

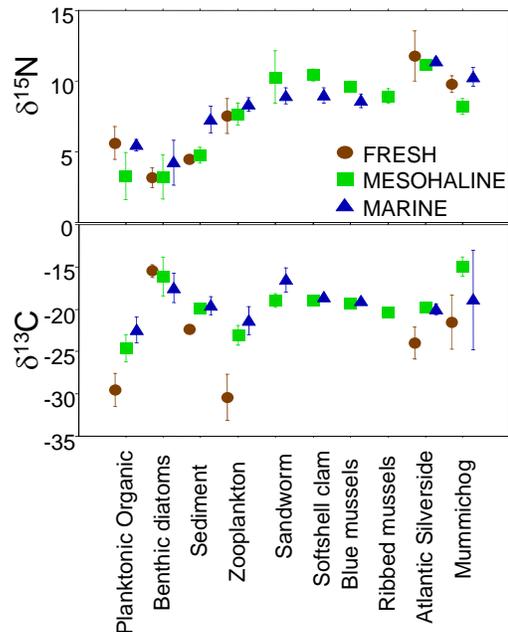


Fig 5-2. C isotopes suggest more variability on the fresh region food web, while N isotopes show the expected increase with higher trophic level.

the meso and marine influenced regions and reflect the riverine particulate organic matter and zooplankton carbon isotope values (Fig 5-2). Because of the variability in freshwater discharge among years, carbon isotope values were more variable among years and organisms in the freshwater region than in the meso and marine regions (Figs 5-1, 2) suggesting that river-influenced areas have higher interannual variability in trophic support compared to marine-influenced areas. We found little difference in nitrogen isotope values associated with location in the estuary, but did find an increase with trophic level (Fig 5-1). Benthic and pelagic food webs and organisms exhibited consistent differences in carbon, and to a lesser extent nitrogen, isotopic values (Fig 5-3). Carbon values for benthic organisms, such as the sandworm and mummichog, were tightly correlated with benthic diatoms, while the values for pelagic organisms were more widespread. Atlantic silverside carbon values indicate approximately 50% of their food is derived from benthic algae. Interestingly, Atlantic silversides had the highest nitrogen isotope value suggested a trophic position higher than mummichogs.

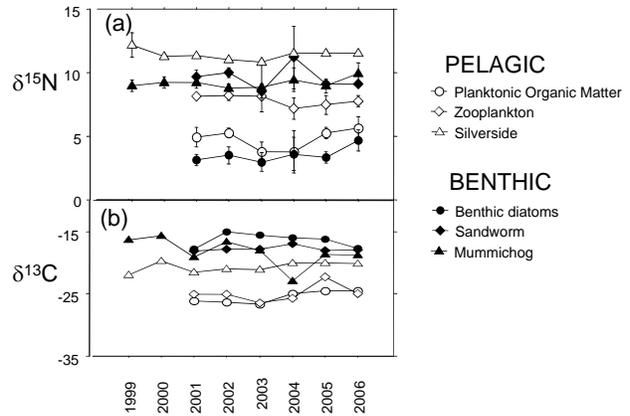


Fig 5-3. C and N isotopes suggest consistent differences between pelagic and benthic based food webs.

(ii) Our field experiments indicate that brackish marshes support higher growth rates and survivorship than salt marshes for mummichogs (Haas et al. in prep.). We used a combination of field experiments and stable isotopes to examine mummichog growth and movement within a New England estuary. Differences in rates at which liver and muscle approach the isotopic value of new diet sources can be used as a way to estimate the time since diet changed (Logan et al. 2006).

Fish growth was significantly different across locations, with the fastest growth at the fresh and marine locations, and slowest growth in the intermediate locations (Table 5-1). The fresh and the most marine locations had the highest insect consumption and most frequent tidal inundation, suggesting that access to the marsh platform and productivity is critical to growth of mummichog.

Location (km reference)	Fresh	Meso1	Meso2	Marine
Mean low tide salinity (ppt)	1.0	12.0	25.0	26.0
Tidal Inundation (%)	14.7	8.2	7.0	12.5
Gut Contents (n)	11	16	24	17
Terrestrial inverts %	28 ± 16.8	3.8 ± 7.2	4.0 ± 7.8	18.2 ± 23.4
Algae & Detritus %	2.3 ± 4.1	36.9 ± 33.9	42.4 ± 27.9	15.3 ± 22.1
Aquatic inverts %	1.4 ± 2.3	1.9 ± 3.6	11.3 ± 20.8	39.8 ± 41.0
Fish growth (n)	22	28	33	37
Length $G_{abs}$ (mm/day)	0.014 ± 0.010	0.009 ± 0.004	0.014 ± 0.021	0.012 ± 0.004
Weight $G_{inst}$ (g/day)	0.207 ± 0.138	0.149 ± 0.058	0.158 ± 0.115	0.188 ± 0.056

When fish were transferred from one location to another, their stable isotope values shifted towards values typical of the current location within a few weeks (Fig 5-4). Wild caught fish showed greater variation in stable isotope values than fish held in cages (Fig 5-5). Some wild

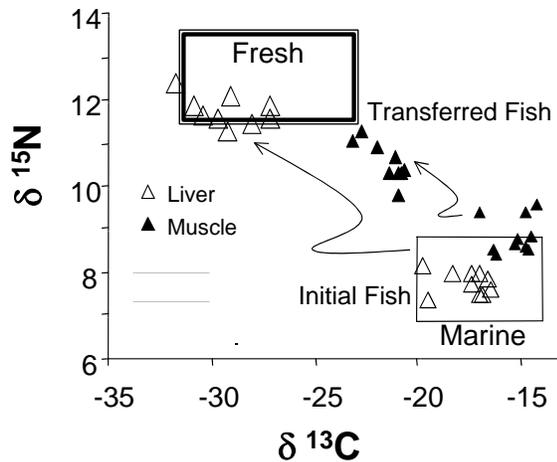


Fig 5-4. Fish transferred among habitats took on the isotopic values of the new location within a few weeks. Stable isotope values for mummichogs transferred from the marine to fresh location are illustrated here.

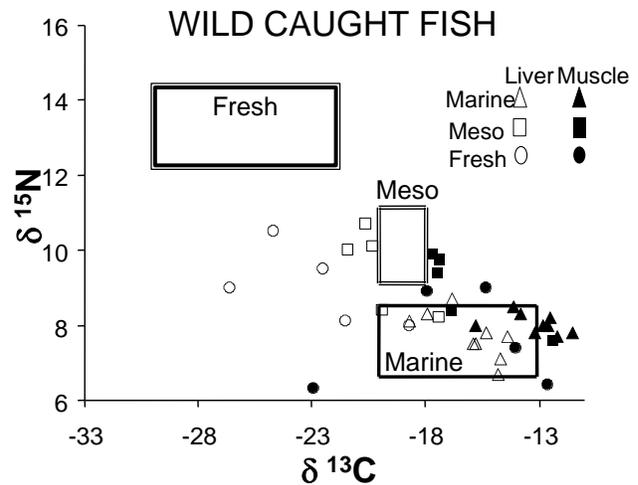


Fig 5-5. Wild caught fish in all areas had isotopic values of meso and marine areas, suggesting fish in the fresh area may have moved in recently.

caught fish showed patterns in muscle and liver stable isotope values that were consistent having recently moved over 10 km, from the most saline location to the freshest location. Intra-season movement of this magnitude was not expected from previous mark and recapture studies.

(iii) Changes in animal species composition may affect the function of saltmarshes because species have important influences on the flow of energy and nutrients in salt marshes. Changes in the animal community could affect the fate and processing of nitrogen in saltmarshes by altering trophic cascades. One abundant, ubiquitous intermediate predator, a small (<10 cm total length) killifish (*Fundulus heteroclitus*, mummichog) has been suggested to control benthic algae through a trophic cascade because they prey on the invertebrates that graze on the benthic algae. In late summer, mummichogs are capable of consuming 3-10 times the creek meiofauna (organisms between 45 and 500  $\mu\text{m}$ ) production. To understand how trophic cascades might operate in a detritus-based ecosystem dominated by an omnivorous fish, we removed mummichog from salt marsh creeks as part of the long-term tidal creek fertilization experiment (TIDE; Deegan et al 2007). These manipulations started in 2004, after 4 years of pre-data collection, and we seek additional funds to continue them for a full decade (6 more years).

In this experiment, throughout a growing season, we enriched an experimental creek (~ 6 ha flooded creek and marsh area) on each flooding tide to 70  $\mu\text{M}$   $\text{NO}_3^-$  and 4  $\mu\text{M}$   $\text{PO}_4^{3-}$  (a 10 x increase in loading above background was achieved), and we removed *Fundulus heteroclitus* (a 60% reduction in abundance of killifish was achieved) from fertilized and reference creeks. This allows us to simultaneously alter interacting components of the marsh ecosystem (creek channels, mudflats, low marsh, high marsh platform).

Counter to the trophic cascade posited in the literature, we have evidence that lower abundance of mummichogs in marsh creeks leads to greater abundance of algae and a greater response of algae to increased nitrogen supply (Fig 5-6; Deegan et al. 2007). Although some significant effects were found on invertebrate abundance, reproduction and community structure in some taxa and habitats, the effects were relatively mild (e.g., no effects were found on species diversity of copepods or annelids). These results suggest that under conditions of high algal productivity killifish switch from carnivory to herbivory to take advantage of an abundant food

source, i.e., algae. These results also suggest that nutrient enrichment may have landscape effects that are not apparent at the plot-level or in short-term experiments that do not incorporate interactive effects with faunal composition.

(iv) Changes to top predator abundance can alter the structure of estuarine and marsh food webs. In northeastern estuaries, striped bass are a key top predator that was severely overfished but which has increased in abundance by an order of magnitude since 1980. Striped bass feed heavily in northern estuaries and have the potential to influence abundance of salt marsh prey such as mummichogs (*Fundulus heteroclitus*). Sixty percent of striped bass diet in the Plum Island Estuary was salt marsh-associated prey (Ferry 2003, Walters et al. 2003). Ironically, this implies that the rebound of striped bass may accelerate the detrimental effects of nutrient enrichment in salt marshes by removing mummichog that controls algae.

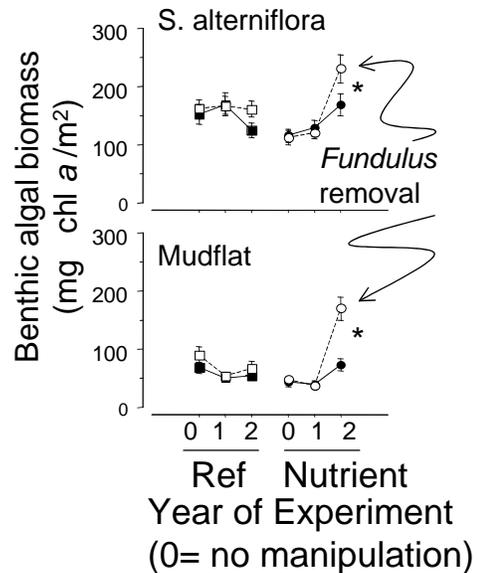


Fig 5-6. Contrary to expectation removal of *Fundulus* resulted in an increase in benthic algae in response to added nutrients.

Nutrient loading and climate change have the potential to control the conditions in the estuary—salinity, temperature, prey abundance—that are the prime determinants of striped bass foraging locations, growth and production. This determines both where striped bass will exert influences over food web structure and where estuarine conditions will lead to high striped bass production.

Before we can address if prey abundance and physical characteristics of the environment interact to create focal points for striped bass foraging, we need to know where and when these predators are feeding, and how often they move between feeding locations. We know striped bass range widely over Plum Island Sound. We now have the technology, using remotely sensed acoustic tagging, to track individual fish and to correlate fish distribution and growth with spatially explicit estuarine conditions. We have been measuring the movement of striped bass, relative to physical conditions (temperature, current, salinity, depth, substrate) using acoustic tags and mobile and fixed receivers in Plum Island Sound.

Over half of the fish tagged (n=14) in 2005 returned to Plum Island Sound in 2006. In 2006, over 2/3 of the tagged fish (n=46) remained in Plum Island Sound for 2 months or more. Individual fish used multiple habitats within PIE, but interesting, fish adopted either a Rowley River or a Plum Island Sound residency pattern (Fig 5-7) and were most frequently detected at a few locations within these areas. This suggests that these fish concentrate at “focal points” within the estuary

(v) New modeling of striped bass population

Use of PIE by Individual Striped Bass, 2005

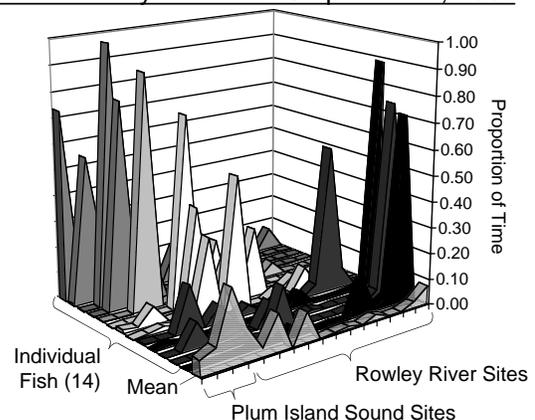


Fig 5-7. Striped bass exhibited a stronger affinity for specific regions of the estuary than expected.

biology is providing critical insight into the response of higher trophic levels to changing estuarine conditions. We have developed an agent-based model of striped bass behavior designed to understand habitat selection, diet, growth and movement of striped bass during their summer feeding stay in New England estuaries (SB-BeMod; [http:// people.umass.edu/finnj/](http://people.umass.edu/finnj/)). Individual-based (or agent-based) models (IBM) have been widely used in the last few years. The challenge is to explain why striped bass choose certain habitats within an estuary, how location choice and growth respond to changing estuarine conditions and how that affects their productivity and availability to fishers. The model is based on a simple patch selection model that has been widely used across taxa. The model uses dynamic programming to find optimal behaviors to maximize growth for each given time and for every state. The hydrodynamic model supplies spatially explicit water current, salinity and temperature fields and the Estuarine Response Model provides whole system production and prey abundance used in the striped bass model. The model can be used to predict the growth and location of striped bass under changing environmental conditions, such as direct influence of hydrodynamics influenced by river discharge or indirect alterations of prey availability due to altered estuarine food webs.

Future Directions: We plan to continue the whole-ecosystem experiments that alter nutrients and predators for another decade, and are seeking funding actively, as this experiment has been costlier per year than the entire LTER. We have found effects of nutrients at levels of enrichment 10 times lower than measured in previous dry ammonium-based fertilizer additions to marsh platforms, suggesting that adding  $\text{NO}_3^-$  via daily tidal flooding is critical to understanding the impacts of N enrichment of coastal waters (Deegan et al. 2007). There is no other experiment in the world that maintains nutrient additions to coastal salt marshes via water. These experiments will become more valuable for understanding the long-term impacts of N enrichment as changes in ecosystem function respond over multiple years.

The critical next step in developing an integrated understanding of striped bass' role in salt marsh-dominated coastal ecosystems, and predicting how striped bass interact with the major drivers of land use and climate, is to couple information on striped bass movement and production with information on the effects of striped bass on ecosystem processes, mediated by their influence on foodwebs. Because striped bass are taken in a fishery, they provide an excellent opportunity to use bioeconomic modeling to link changes in ecological processes, through their influence on striped bass populations, to an economic impact. Striped bass also provide a critical link with society and a motivation for sound estuarine management to sustain the striped bass fishery. Striped bass are the basis of lucrative recreational fishery – over 40 % of the Atlantic coastal recreational catch occurs in Massachusetts.

## INTEGRATION AND SIMULATION MODELING

A research program that involves as many disciplines and facets as the Plum Island Ecosystems LTER requires several approaches to insure effective integration across programmatic areas. Our overall research question is broad, involving i) human populations, ii) biogeochemical fluxes and transformations in the atmosphere, watersheds, estuaries and the ocean, and iii) food webs with a structure and function that reflects interaction with their environment. The flow diagram and spheres of influence figures (Figs 6 & 8) of the Introduction provide a conceptual framework that synthesizes our understanding of the effects of organic matter and nutrient inputs on trophic structure and function and it illustrates how the major research questions and programmatic areas in this proposal fit together. We are using several approaches to integrate across programmatic areas, including: 1) synthetic projects that cut across multiple program areas, 2) long-term experiments aimed at changing the primary production resource base, 3) cross-system comparisons, 4) synthetic review papers, and 5) simulation modeling.

**1. Synthetic projects:** There are three projects that have been underway for several years or are about to start that cut across multiple program areas within the PIE LTER. By cutting across program areas, they directly link the research activities from different parts of the LTER program, help identify cause and effect relations, and thereby promote synthesis at different hierarchical levels.

The longest running project is the tidal creek fertilization and fish removal experiment, locally called TIDE. A primary goal of the LTER is to predict how changes in the relative loading of inorganic and organic N loading will affect the estuarine ecosystem structure and function. The TIDE project enables us to investigate the effects and fate of inorganic N in headwater tidal creeks quantitatively. The project also enables us to quantify the interactions of increased nutrients ( $\text{NO}_3^- + \text{PO}_4^{3-}$ ) and reduced abundance of a key fish species on salt marsh ecosystems. This ongoing multi-year experiment is being conducted on two matched pairs of tidal creek ecosystems ( $\sim 120,000 \text{ m}^2$  study units) in the extensive salt marshes of the Plum Island estuary (Fig 6-1). Throughout a growing season, we add nutrients to each twice-daily flooding tide of one creek per pair to mimic surface water nutrient pollution of marsh ecosystems ( $70 \mu\text{M NO}_3^-$  and  $4 \mu\text{M PO}_4^{3-}$  - a 10 x increase in loading above background). We also remove a mid trophic level predator (*Fundulus heteroclitus*;  $\sim 60\%$  reduction in abundance of mummichog) from half of each of the marsh/creek complexes ( $60,000 \text{ m}^2$ ). This allows us to simultaneously alter interacting components of the marsh ecosystem and examine the response of plants, animals and biogeochemical processes to the sustained manipulations.

One of the more interesting results suggests the mummichog may be a weak interactor due to its omnivorous nature. Behavior-mediated effects on species interactions are now recognized as important mechanisms in food web dynamics (Werner & Peacor 2003). For example, omnivory may add stability by preventing a trophic cascade despite a significant reduction of a top

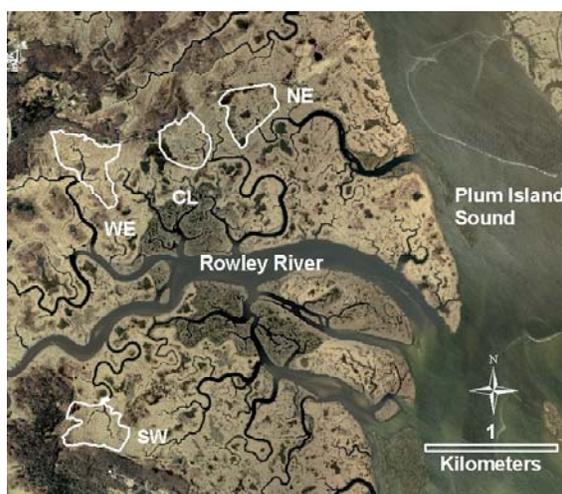


Fig 6-1. Experimental paired tidal creek systems in the Plum Island Estuary.

predator/omnivore. (see Q5; Deegan et al. 2007). In our food web, the removal of mummichogs apparently altered the behavior of grass shrimp, allowing them to feed more actively (Johnson, Ph.D. student, LSU) and at a higher trophic level in the marsh creek (Fig 6-2; Galvan, Ph.D. student, LSU).

Our whole-ecosystem  $^{15}\text{N}$  additions are revealing ecologically significant differences in N-cycling between N-enriched and control marshes, including a decline in ecosystem N retention (30 - 50% of incoming N) compared to reference systems (70 - 90%, Fig 6-3). Although the total amount of  $\text{NO}_3^-$  retained was much higher in the fertilized marsh, the response to loading was not linear, indicating the marsh may be saturated with respect to  $\text{NO}_3^-$  (Fig 6-4). In the fertilized creek, the retention of  $^{15}\text{N}\text{-NO}_3^-$  was higher than bulk  $\text{NO}_3^-$  (48% compared to 30%) suggesting an additional, marsh-derived source of  $\text{NO}_3^-$ .

The fate of the nitrate retained in the marsh is being assessed in measurements of biota, sediments and denitrification. Changes in  $^{15}\text{N}$ -tracer content suggest plant  $\text{NO}_3^-$  uptake is 2 to 3

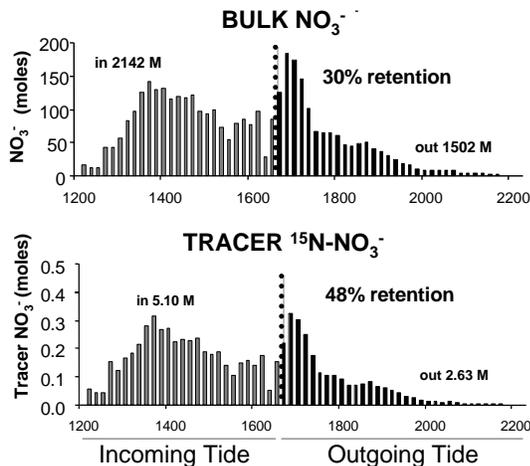


Fig. 6-3. Comparison of bulk and tracer  $\text{NO}_3^-$  budgets over a tidal cycle.

fold higher in the fertilized creek than in the reference creek (Fig. 6-5), resulting in higher N content and biomass of *S. alterniflora* in the fertilized marsh. Overall the efficiency of  $^{15}\text{N}\text{-NO}_3^-$  retention by plants or by the entire marsh ecosystem is lower in the fertilized (3%) compared to the reference marsh system (3% vs. 7%). Another fate of the added N may be loss via denitrification. Initial work suggests that direct denitrification in the creek, but not the marsh platform, is stimulated by added nutrients (Koop-Jacobsen, Ph.D. Student, Boston University).

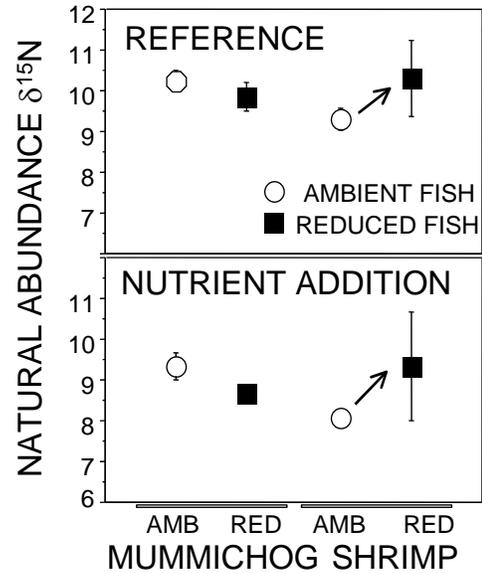


Fig 6-2. Higher  $\delta^{15}\text{N}$  values suggest that shrimp have changed their behavior with mummichog reduction, foraging more actively and at a higher trophic level.

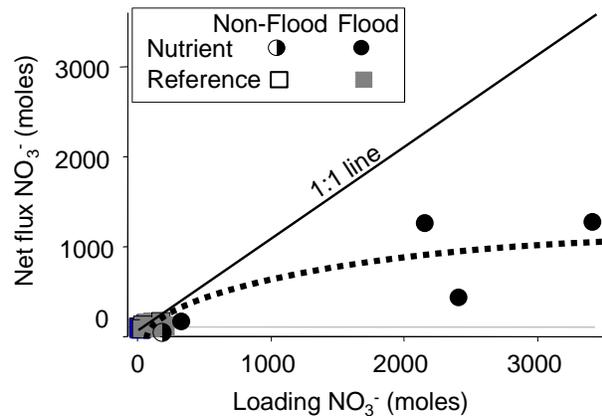


Fig. 6-4. Fertilized marshes retain more total  $\text{NO}_3^-$  but retention is not proportional to loading, suggesting that these marshes may be saturated.

Our unique approach has found effects of nutrient enrichment at levels 10 times lower than used in previous dry fertilizer additions to marsh platforms, suggesting that adding  $\text{NO}_3^-$  via daily tidal flooding is critical to understanding the impacts of N enrichment of coastal waters. We currently have 4 years of data, but additional years of fertilization are needed to determine if the effects are sustainable and what impacts they will ultimately produce. These changes in marsh structure and function are being incorporated into an ecosystem model to predict the long-term fate of marshes in response to sea level rise in the face of increased nutrient loading (See modeling section).

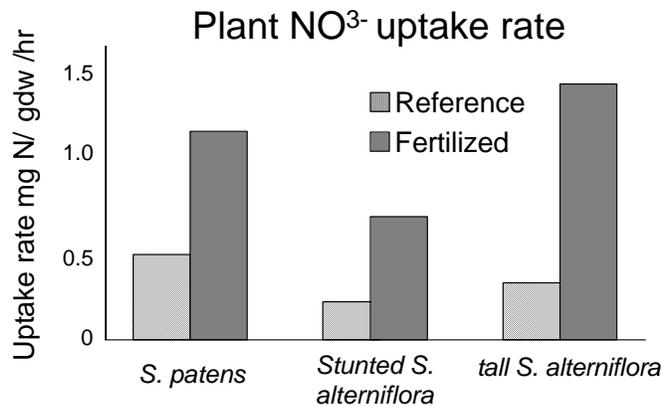


Fig 6-5. Marsh plant uptake rates were 2-3 fold higher in the fertilized marsh compared to the reference marsh.

The river herring project is another synthetic, cross-cutting activity that links research conducted on higher trophic levels in the estuary to our watershed interests. Begun just a year ago, UMass scientists and students are trying to understand the cause of declining anadromous fish runs in the Ipswich River. Habitat availability, or lack thereof, is a key suspect. Interestingly, human activities are responsible for greatly altering river flow and water levels, which are strong determinants of habitat quality, not only for higher trophic levels but also for biogeochemical processing of N inputs to riverine systems. Closely related to the herring project, is a Biocomplexity Project that will commence this fall. This too is a cross-cutting project that will not only bring in social science to PIE LTER research, but also link human, watershed and estuarine components of LTER research.

These synthetic, cross-cutting projects enable us to study the interactions of human activities and vulnerabilities, hydrology, land use change, sea level rise, nitrogen biogeochemistry and estuarine food web structure all at the same time and at the natural watershed and estuarine scale. These projects cut across all programmatic areas from the watershed to higher trophic levels and the marsh. The information from these projects and experiments is being (is to be) synthesized in several simulation models of human activities, watershed hydrology and biogeochemistry and estuarine foodwebs and N dynamics.

**2. Changing the primary production resource base – long-term experiments:** One of the two overall hypotheses of the PIE LTER deals with the relative importance of inorganic N vs organic N inputs to a system. Systems driven by allochthonous, usually low quality organic matter inputs are likely to have a very different trophic structure and food web efficiency than ones driven by autochthonous algal production. The water column programmatic area focuses heavily on these issues. Two long-term experiments are underway that should produce large differences in the relative inputs of high and low quality organic matter: detrital removal (via haying) and detrital and algal production (via tidal creek fertilization).

For the detrital removal experiment, we are using extensive areas of the marsh that are hayed on a regular 1 or 2-year cycle (haying is a traditional activity on the PIE salt marshes since colonial times). We have established the haying history of the region and established a working relation with one of the major remaining hayers in the country (Dan McHugh). Results show that this

practice favors *Spartina patens* at the expense of *S. alterniflora*. Furthermore, haying increases plant stem density, decreases standing biomass, stimulates N fixation and sulfate reduction, and has short term impacts on the marsh invertebrate community and benthic algae (Buchsbaum et al., in review).

For the marsh and creek algae fertilization experiment, we are taking two approaches. The TIDE experiment (explained above) adds nutrients to a tidal creek (2 with adequate levels of funding) that floods the marsh platform on high tides. The other approach we're taking is in collaboration with the Town of Ipswich, which discharges secondary treated sewage into a small tidal creek. Neither of these approaches is totally satisfactory. The former is extremely costly and can be sustained only with supplemental funding (the TIDE project was funded at about \$850k per yr). The latter "experiment" is not replicated and freshwater additions confound interpretation of the "fertilization".

**3. Cross-system comparisons:** cross-system comparisons and experiments are often important steps in understanding the generality of findings developed at single sites. Investigating the effects of sea level rise, tidal range, and climate on salt marsh productivity and accretion, Jim Morris is conducting experiments similar to those at PIE at sites in South Carolina, the Gulf coast and the West coast. Bruce Peterson is a key player in LINX (lotic intersite N experiment), a project seeking to understand the effects of land use change (urbanization and agriculture) on stream N dynamics. Experiments are being conducted at PIE and 7 other biomes in the US. Martha Mather has been studying striped bass in the Plum Island estuary for many years. Her studies are not confined to PIE however and extend along the entire Massachusetts shoreline including both Acadian and Virginian biogeographic provinces. The PIE LTER has also interested Mitch Sogin at the MBL Bay Paul Center for molecular evolution to study the diversity of marine microbes by conducting a comparative sampling across all the coastal LTERs. This project is commencing this fall. Wil Wollheim and Charlie Vorosmarty and colleagues have developed an approach, grounded in stream spiraling theory, that identifies the individual and conjunctive roles of biological and hydrological properties controlling nutrient removal in benthic dominated rivers. They used this approach to evaluate river size dependence of biological activity in several existing river network nitrogen (N) models. They then applied the approach in an idealized river network to explore how biological activity, river network geomorphology, and surface water hydraulics interact to define nutrient removal in full river networks, comparing results across multiple systems. Finally PIE LTER scientist, Chuck Hopkinson, has been involved with others from the LTER Network in trying to establish continental-scale networks involving LTER (and other) sites to examine the effects of sea level rise and hurricanes on the ability of coastal wetlands and inland forests to provide ecosystem services and to examine the effects of urbanization and N pollution on ecosystems across the North American continent.

**4. Synthetic, review papers:** PIE scientists have led or participated in several comprehensive reviews of broad topical areas in watershed and estuarine science, drawing extensively on research conducted by others as well as from within the LTER. These synthesis papers provide in-depth analyses of the current understanding of various topics and help to establish the main scientific questions and challenges that face scientists working in these fields.

**NRC 2000:** an NRC publication that explains the technical aspects of nutrient over-enrichment in coastal ecosystems, and proposes both local action by coastal managers and a long-term national strategy incorporating policy design, classification of affected sites, law and regulation, coordination, and communication.

**Driscoll et al. 2003:** a series of articles, white papers and briefings in Washington, D. C., discussing the environmental consequences of the enhanced availability of reactive nitrogen to ecosystems of the northeastern U.S. and the globe.

**Hopkinson and Smith 2004:** a review of benthic, pelagic and whole system respiration in estuaries. Information on the factors controlling respiration is presented and challenges in determining the relative importance of allochthonous and autochthonous sources of organic matter fueling estuarine metabolism are identified.

**Fagherazzi et al. and Torres et al. 2005 and 2006:** an overview of a Chapman Conference focused on salt marsh geomorphology (conference organized by Fagherazzi, Torres, van Proosdij and Hopkinson). This conference held in Nova Scotia in fall 2005 discussed the factors likely to influence the future of coastal intertidal wetlands worldwide.

**Farber et al. 2006:** a review paper presenting the merits of using an ecosystem services-based approach to managing ecosystems, using examples from LTER sites.

**Wollheim et al. 2006:** a paper that presents a conceptual approach for evaluating the biological and hydrological controls of nutrient removal in different sized rivers within an entire river network. The paper explores how geomorphic, hydraulic and biological factors control the distribution of nutrient removal in an idealized network.

**Hopkinson and Giblin 2007 - in press:** a review of the N cycle and dynamics in salt marsh ecosystems and suggestions for future research directions.

**Mulholland et al. in review and Beaulieu et al in prep:** papers summarizing the impacts of land use change on denitrification in urban, agricultural and reference streams of eight biomes throughout the U.S.

**Battin et al. in review:** a synthetic paper that combines recent progress from geophysics, microbial ecology, and organic geochemistry in a conceptual framework to better understand the mechanisms that underlie global carbon fluxes from the land to the ocean.

**5. Simulation Modeling:** Modeling is an essential component of our program used to integrate both within and across programmatic areas. Simulation modeling (1) ties together field observations and experiments across space and time permitting a whole systems perspective, (2) allows us to test hypotheses and understanding of mechanisms governing ecosystem processes, and (3) provides whole system prognostic capabilities. In each **programmatic area, models** are used to enhance and test understanding of specific experiments or mechanisms governing the process under study. 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. Below we highlight three of the major synthetic and simulation accomplishments to date.

**Watershed Modeling -** We currently employ the USGS-EPA hydrological simulation program - Fortran (HSPF) to model watershed hydrology and terrestrial and aquatic biogeochemistry (Filoso *et al.* 2004, Kirkby *et al.* 2000, Zariello and Ries III 2000). HSPF has several strengths,

including integration of the entire watershed, good skill in predicting stream and tributary hydrology, and comprehensive models for upland and aquatic biogeochemical processes; however, it suffers from extensive over parameterization of biogeochemical processes. As a result, our current primary objective is on developing simplified watershed biogeochemistry models that require minimal parameterization, which will facilitate implementation in other watersheds where extensive observations may be lacking. The simplified modeling focuses on identifying the dominate mechanisms first, then implementing them with minimal parameterization, which leads to better understanding of watershed biogeochemistry that ultimately drives the oligohaline portion of the PIE estuary. While currently our watershed and estuarine models operate independently, we plan to couple these models in the long-term.

**Estuarine Modeling: Hydrodynamics** - We have developed and implemented several hydrodynamic transport models in the PIE estuaries at various spatial and temporal resolutions. Our simplest model is a 1D, tidally average model that has been extensively used to examine various aspect of estuarine metabolism (see below). Our tidally explicit models include a branched 1D model using USGS' Full Equations Model (FEQ), a 2D depth average finite element model that uses a diffusive wave approximation (Ip *et al.* 1998) for the shallow water equations and incorporates a groundwater model to handle wetting and drying of the marsh platform (see <http://eco37.mbl.edu/kinematic>). Recently, we have been collaborating with Changsheng Chen of UMASS Dartmouth to implement FVCOM

(<http://codfish.smast.umassd.edu/>) at PIE. FVCOM employs an unstructured grid, finite-volume, three-dimensional (3D) primitive equations ocean model for the study of coastal oceanic and estuarine circulation (Chen *et al.* 2003, Zheng *et al.* 2003). The transport component of FVCOM is now running (Fig. 6-6); however, it remains to be calibrated with velocity observations from ADCP (Acoustic Doppler Current Profiler) deployments and salinity surveys to account for baroclinic circulation.

We are currently implementing an estuarine biogeochemistry model in FVCOM for PIE that is based on EPA's QUAL2E program. Field observations and YSI water quality sonde data will be used to calibrate the model, which will serve as our modeling benchmark. We also plan on developing and testing a thermodynamically constrained metabolic model for estuarine biogeochemistry (see below) that we will compare to our modeling benchmark.

**Advancing Theoretical Modeling** - As a consequence of our combined modeling and

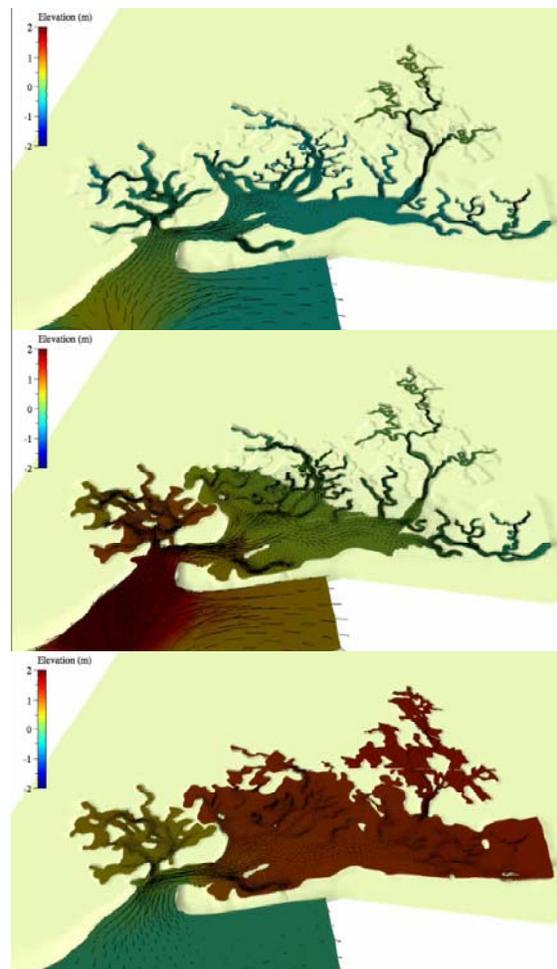


Fig 6-6. FVCOM run in PIE near low tide (top), mid tide flood (middle) and full tide ebb (bottom).

experimental approaches, we have identified a general problem facing conventional biogeochemical modeling approaches. In natural ecosystems, changes in community composition occur as environmental drivers changes, such as occurs with eutrophication or climate change. Existing biogeochemical models are based purely on empirically derived expressions and, except for conservation of mass and energy, lack fundamental principles that govern how living systems organize to processes mass and energy. As a consequence, models must be re-parameterized following changes in community composition that results from alterations in external drivers, which renders model extrapolations to conditions not already observed dubious. To improve model robustness to changes in community composition, we are developing and testing new theoretical approaches based on nonequilibrium thermodynamics. In particular, current theories indicate that nonequilibrium systems with sufficient degrees of freedom organize towards maximum entropy production (MEP) (Dewar 2003, Dewar 2005, Lorenz 2003). To implement MEP within a biogeochemical context, we have developed a distributed metabolic network perspective for ecosystem processes (Vallino 2003). The metabolic network utilizes resources and energy from the ecosystem to build biological structure

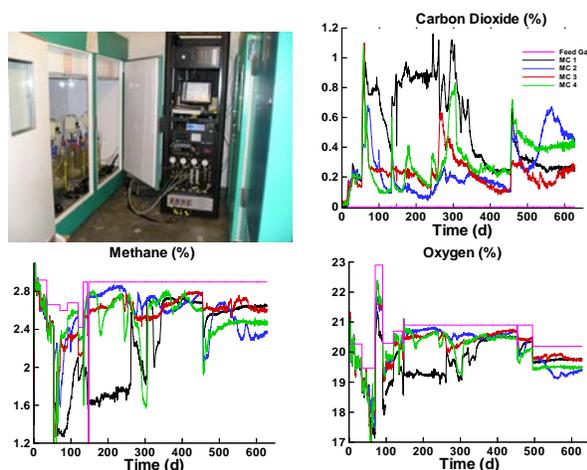


Fig 6-7. Methanotroph microcosm (MC) setup (upper left), and gas concentrations (%) of input (purple) and output gasses of the four MCs (black, blue, red green) for CO<sub>2</sub>, CH<sub>4</sub> and O<sub>2</sub> for over 630 days).

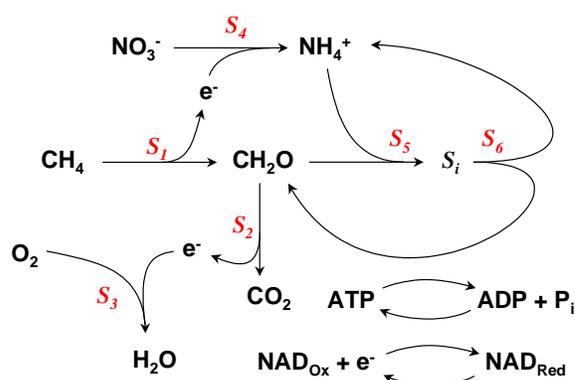


Fig 6-8. Simple distributed metabolic network for a methanotrophic-based food web. Six biological structures,  $S_i$ , catalyze the reactions.

in the form of enzymes that catalyze the metabolic reactions. Maximizing entropy production governs allocation of biological structure; consequently, as resources are consumed or environmental conditions change, allocation of biological structure changes to meet the MEP objective criterion.

Although our long-term objective is to implement the MEP constrained metabolic network within our PIE transport models, we are currently using methanotroph-based microbial community microcosms as experimental systems to facilitate development and testing of the MEP approach (Fig 6-7). A simplified metabolic network represents the entire microbial community, including methanotrophs, general heterotrophs, viruses, and protist grazers (Fig 6-8), where synthesis and allocation of biological structure,  $S_i$ , is governed by MEP over a specified integration interval. Based on MEP, the model predicts concentration of nutrient resources, metabolic reaction rates, biological structure allocation and concentration, and reaction thermodynamic efficiency (Fig 6-9). Our objective it to predict dynamics observed in the microcosms experiments (Fig 6-7) based on MEP, which includes employing molecular

methods to ascertain how metabolic function is allocated in the experimental system that can be compared to model predictions.

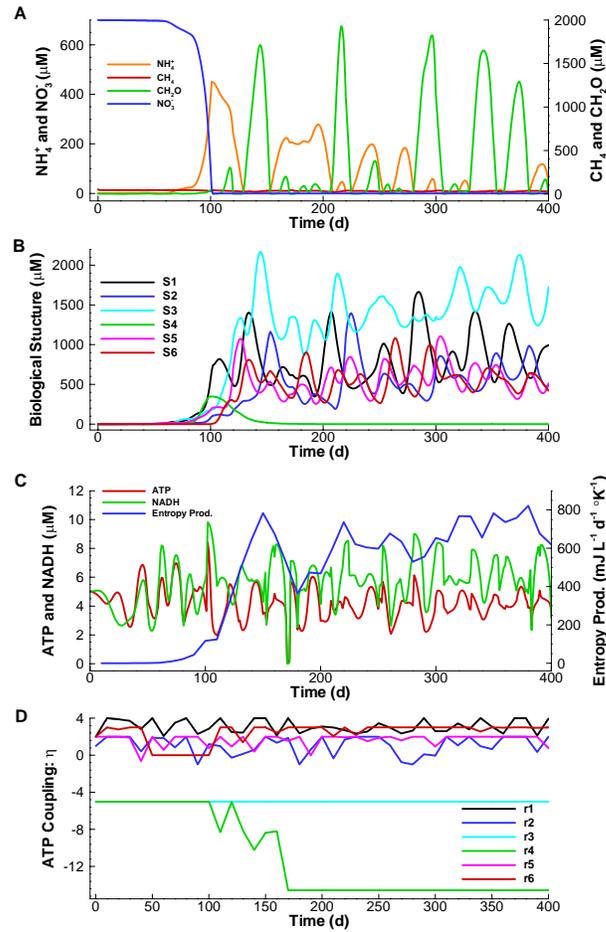


Fig 6-9. Concentrations of (A) nutrients and (B) biological structures, (C) internal ATP and  $\text{NAD}_{\text{Red}}$  concentrations and entropy production, and (D) ATP reaction coupling,  $\eta$ , control functions for 400 day simulation.

## **DATA INFORMATION AND MANAGEMENT**

### **INFORMATION MANAGEMENT**

The goal of the PIE LTER data and information system is to provide a centralized network of information and data related to the Plum Island Sound Estuarine Ecosystem and its watersheds. This centralized network provides researchers associated with PIE-LTER access to common information and data in addition to centralized long-term storage. Data and information are 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 Microsoft Windows server with level 3 raid, which is backed up on tape nightly. Once a month a tape is removed and stored in a separate building.

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 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, published and unpublished papers, reports and School Yard education. The data section is broken down into four sections consisting of Program Areas, Education and Outreach, Physical Characteristics and Database Links. PIE maintains an internal database archive of datasets from which the home page is updated annually. Datasets on our web site are updated more frequently as investigators add data. The organization of the PIE home page basically mirrors the internal database archive in nomenclature, which allows for easy updating of datasets.

### **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 additional research assistants associated with program areas. The team has the necessary leadership, knowledge and technical expertise for creating and maintaining the PIE LTER research information. Hap Garritt, a senior research assistant with The Ecosystems Center, MBL, has been the information manager (IM) since 1998 and has the responsibility for overseeing the overall integrity of the data and information system for PIE-LTER. Hap has 25 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 release 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. We have migrated from a Microsoft Word metadata template to a Microsoft Excel spreadsheet template. The Excel template was developed by Jim Laundre, ARC LTER and has been adapted for PIE to allow for consistent metadata entry and subsequent conversion via a visual basic macro to XML structured Ecological Metadata Language (EML) according to EML Best Practices for LTER Sites. Individual researchers are responsible for quality assurance, quality control, data entry, validation and analysis for their respective projects. Researchers are reminded about contributions to the database several times during the year via email or during field sampling trips, in addition to announcements during our Annual Spring PIE-LTER All Scientists Meeting.

#### **DATA ACCESSIBILITY AND TIMELINES**

Researchers on the PIE-LTER 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 release 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 7-1. 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, crawlers and web hits not associated with browsing, indicates that our on-line data sets are viewed extensively. On average during 2006 PIE had more than 15,000 hits/month on our home page, more than 5,000 hits/month on our Programmatic Area data pages

#### **NETWORK PARTICIPATION**

The PIE LTER program participates in the annual LTER Information Managers meetings, contributes to network level databases of ClimDB, HydroDB, Personnel, Bibliography, Site DB, Metacat Data Catalog and Trends and has been involved with LTER Network EML workshops. Hap Garritt is on the LTER IM Executive Committee (2007-2010) and is a member of the Unit

Dictionary and GIS Information Manager working groups. Chuck Hopkinson is on the LTER Network Information System Advisory Committee (2005-2009).

### **CURRENT IM PROJECTS**

We are currently updating our existing on line EML level 2.5 metadata to EML level 4-5 using the MS Excel based template. We are in the midst of adding extensive datasets from the Tidal Creek fertilization experiment TIDES project and from stations pertinent to PIE LTER watersheds available from the NOAA National Climate Data Center Weather Cooperative and the National Atmospheric Deposition Program. Development of a GIS information system for sharing PIE LTER GIS data has been an on going project for many years as we are attempting to bridge three GIS softwares (ArcGIS, IDRISI, RiverGIS). The current LTER IM GIS working group is also discussing a centralized shared platform for GIS information as many LTER sites need a better way of viewing available GIS information at the site level and network level. We are also in the midst of redesigning our web site, the third time in 9 years.

### **FUTURE OBJECTIVES**

Large streaming datasets associated with short sampling interval (15 min) weather and water quality station data loggers will require us to develop a database system capable of managing multiple year aggregations of data. The LTER Network as a whole and other planned observatory networks (AEON, NEON, ORION) are also in the midst of brainstorming how to cope with the vast amounts of data that will be forthcoming with these new environmental observatory initiatives. PIE has been and plans to continue to be involved in environmental observatory associated workshops.

Table 7-1. Monthly use of the PIE LTER Web Site during 2006 summarized from analyses of the PIE web server log files. Use is represented as the number of times a web page has been accessed <sup>a</sup> (hits).

Year 2006	Hits on PIE Homepage		Hits on PIE Programmatic area data	
	All Hits	Non-MBL Domain	All Hits	Non-MBL Domain
JAN	15,427	14,346	5,365	5,066
FEB	13,692	12,946	4,652	4,597
MAR	16,681	15,532	6,003	5,703
APR	17,554	16,785	5,961	5,831
MAY	16,596	15,434	5,868	5,585
JUN	14,640	13,841	5,045	4,794
JUL	16,754	15,067	6,106	5,732
AUG	16,116	15,248	4,675	4,582
SEP	18,917	18,038	5,779	5,628
OCT	17,773	16,995	5,023	4,899
NOV	19,932	19,456	7,007	6,981
DEC	12,070	11,500	4,446	4,318
Annual Total	196,152	185,188	65,930	63,896

<sup>a</sup>Non-browsing activity web hits have been excluded using filters for spiders, crawlers and domains not representing normal browsing activity.

## LTER NETWORK ACTIVITIES

PIE LTER has established numerous linkages with other LTER sites and the LTER network. We have hosted and co-organized network-wide meetings, initiated new network-wide intercomparison projects, organized science symposiums, served on steering committees for several intersite and network activities, participated in LTER Planning Grant development and worked to involve LTER interests and sites within the NEON and CUASHI programs.

PIE scientists have participated at a variety of levels in network-wide committees. IM manager, Hap Garritt, has been a member of the unit dictionary and GIS Information Managers working groups, and is currently a member of IM EXEC. Charles Hopkinson has been the site representative on the Coordinating Committee and is currently a member of the Executive Board. He also represents the research community on the Network Information Science Advisory Committee (NISAC).

PIE scientists have been frequent participants in the annual mini-symposiums held at NSF in Washington, DC each winter. For the 2003 mini-symposium, Hopkinson spoke on the subject of linking social science with land-water interactions. He co-organized (with Ducklow and Reed) and spoke at the coastal/marine science mini-symposium in March 2005. This past winter (2007), he co-organized (with Carpenter and Grove) the mini-symposium featuring the linking of social and ecosystem science in the LTER network. In 2004, Gil Pontius participated in another mini-symposium featuring social science, speaking on the issue of land use change modeling.

Comparative and cross-site research has been a strong theme in PIE research. In addition to comparisons across systems within our own research program, PIE scientists have been involved in several cross-site experimental and synthesis activities that involved multiple LTERs. Bruce Peterson has been involved in the LINX (Lotic Interstream Nitrogen Experiment) cross-site stream experiments, serving on the executive committee of LINX II, which compared N cycling dynamics in “disturbed” agricultural and urban systems across the country (Fig 8-1). The Plum Island Sound watershed was one site across 8 biomes in the US chosen for intensive experimentation. The experiment involved the use of  $^{15}\text{N}$  tracers to determine nitrate uptake and denitrification in forested, agricultural and urban streams in the Ipswich and Parker River watersheds. The goal was to improve our ability to predict the extent of nitrogen processing in streams and its relationship to land use patterns in the watershed. Chuck Hopkinson participated (2003-2005) in an LTER-initiated and NCEAS funded project examining the use of an ecosystem services-based approach to guiding natural resource management (Farber et al. 2006). This activity and PIE’s involvement continues with additional funding from the Moore Foundation to BES scientist, Bob Constanza, at UVM. Another project, initiated at the Salt Lake City All-Scientists Meeting workshop, has been studying organic matter preservation in soils and sediments. PIE scientists, Jim Morris and Chuck Hopkinson, took the



Fig 8-1. PIE scientists Bruce Peterson and Suzanne Thomas working with Jody Potter from UNH on a tributary of the Rio Icacos, a Luquillo LTER LINX-II site.

initial lead in developing this intersite, comparative study into the controls on organic matter storage in soils and flooded sediments. We were successful in obtaining network office funds to expand these activities for several years. The group is now preparing a manuscript summarizing findings under the direction of Chris Craft from the Georgia Coastal LTER. Finally PIE scientists are always well represented at the LTER all-scientists meetings. In the 2003 meeting in Seattle, Anne Giblin was one of the invited plenary speakers.

PIE scientists have also played an active role in the ongoing LTER network-planning grant. With NSF funds the LTER network is actively developing a strategic plan for LTER that will raise social science to be an equal partner in ecosystem research at LTER sites as well as promote much more extensive intersite, cross-site, synthetic and regional science in the LTER program. Liz Duff, our schoolyard director, has participated in several educational committee strategic planning meetings and has been working on including science from the Arctic and Harvard Forest LTERs into her K-12 activities. Gil Pontius has been an active player in incorporating social science into the strategic plan, participating in mini-symposia at NSF and attending and organizing workshops. Chuck Hopkinson organized a workshop with Deb Peters from the Jornada LTER to discuss the role of simulation modeling as a means of promoting synthesis within the LTER network. Joe Vallino actually represented PIE at the modeling workshop in Las Cruces in Aug 2006. Joe Vallino also attended the many workshops on developing “human – natural system loop-diagrams for the strategic plan. Finally Hopkinson organized along with David Foster and Charlie Driscoll a joint New England (and potentially Baltimore) LTER meeting / workshop to discuss regional collaborations as a means of promoting synthesis as a component of the strategic plan.

NEON (National Ecological Observatory Network) has also been a component of PIE’s LTER network activities. Our participation was mostly focused on trying to involve as much of the LTER network into NEON as possible. Monitoring ecological systems is a major component of all LTERs so it made sense to try to involve LTER sites as NEON sites. Towards this involvement PIE scientist John Hobbie organized a meeting to discuss simulation modeling as a synthetic tool within NEON. Gil Pontius, Joe Vallino, and Charlie Vörösmarty attended the workshop. Hopkinson and Hobbie attended the 3C’s NEON planning meeting at Las Cruces in 2006 with the goal of developing 2 continental scale gradient networks, one involving suburbanization, land use change and N deposition gradients and another involving the effects of sea level rise and hurricanes on the ability of coastal wetlands and inland forests to provide ecosystem services. RFIs submitted on these subjects recommended the inclusion of several LTER sites into proposed networks (urban/rural RFI led by Nancy Grimm with Hopkinson as 1 of 6 other contributors and coastal wetland/ hurricane RFI led by Chuck Hopkinson with 4 other LTER scientists (from Puerto Rico and Georgia coastal) and many out-of-LTER-network contributors).

Finally PIE LTER has also been involved in the Consortium of Universities for the Advancement of Hydrological Sciences (CUAHSI) through Charlie Vörösmarty. Vörösmarty has received funding by NSF to spearhead a regional synthesis center with the primary goal to quantify the widespread alteration of hydrologic systems over local-to-regional domains focusing on the Northeast corridor of the United States over a 500-yr period (1600 to 2100). This effort also involves Co-PIs L. Band, D. Lettenmaier, and R. Vogel,

A working group will study Regional Watersheds, Hydromorphology, and Continental Processes, for the purpose of carrying-out synthesis activities and serving as a test-bed for ideas

on how to optimally execute synthesis. The Northeast corridor is the focus area because it offers a data rich environment bearing a long history of human interaction with ecohydrologic systems. The presence of four LTER sites (Hubbard Brook, Plum Island Estuary, Harvard Forest, and the Baltimore Ecosystem Study) and other intensive research sites embedded within larger watersheds provides a context for spatial scaling and for investigating the 500-year history of hydromorphic evolution of regional watersheds. Three of the LTER sites incorporate integrated studies of historical ecohydrologic, land use, and societal change. Three of the sites (HB, PIE, BES) include intensively instrumented, nested watershed systems, while two (HF and BES) include eddy flux towers in forest and urbanized landscapes. All sites incorporate a gradient from forest to urban sites, with comprehensive information and research programs on water, carbon, nutrient cycling. Comprehensive environmental histories of colonization, industrialization, urbanization/suburbanization also help to ensure detection of strong signal-to-noise relationships. Ongoing studies of land-to-coastal ecosystem coupling (e.g. Ipswich River / Plum Island Sound and Chesapeake Bay studies) also argue for the region as an important testbed to assess human impacts on major economically important environments of an entire region.

## EDUCATION AND OUTREACH

The PIE LTER has developed links with local teachers and students, citizens, conservation organizations, and local, state and federal agencies. We support a broad, well-rounded suite of activities. We expect our education/outreach program to further expand, as we actively seek additional support from other federal agencies (e.g., NOAA), 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.

**LTER Schoolyard:** This program has been highly successful as a result of collaboration with Mass Audubon and the Governor’s Academy, and additional NSF funds (EdEn and Expanded Schoolyard supplements.) Teachers at the Governor’s Academy, especially Susan Olezsko, implement 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.thm>). Mass Audubon has implemented, with partial support from the LTER, a 5<sup>th</sup> –12<sup>th</sup> grade science education program “The Salt Marsh Science Project” (<http://www.massaudubon.org/saltmarsh>). This program focuses on the invasion of *Phragmites australis* in salt marshes. Under the guidance of Mass Audubon, students monitor transects to analyze vegetation changes, and measure porewater salinities in relationship to the vegetation. Students monitor the spread of invasive species including the common reed (*Phragmites australis*) and purple loosestrife (*Lythrum salicaria*) and study fish communities. Students’ research has paralleled that of LTER and collaborating scientists. SMS serves an average of 1000+ students per year and 40 teachers from 11 schools per year.

Mass Audubon’s Education Coordinator and LTER education Representative, Elizabeth Duff, trains local teachers in the field protocols, classroom lessons, and data entry and analysis procedures. Duff works in partnership with these teachers, implementing the SMS program. On field trips, students collect real data of interest to scientists. Scientists assist with data analysis, interpretation and feedback. An annual conference, allows participants to share their findings, and to learn from each other. Student data is shared via the SMS web site.

**Reaching a Broader Community:** In addition to maintaining this highly successful Schoolyard program, Duff has helped forge links between teachers and PIE-LTER research and local school curriculum. Since 2004, 20 teachers have attended the PIE-LTER All Scientists Meeting (ASM). At ASM workshops teachers have connected with PIE researchers - brainstorming ways research connects to the Massachusetts Science Frameworks, and discussing ways that LTER scientists can help support teaching goals. To help teachers better understand the scientific presentations and to help researchers better communicate with a lay audience (i.e., drop the jargon), we developed a glossary of scientific terms, and developed and presented a PowerPoint slideshow with suggestions for scientists presenting to non-scientists. From the brainstorming sessions, we identified several PIE-LTER research areas best suited for connecting to schoolyard and local educational programs. We developed and delivered 3 courses on climate change and coastal

communities, with 4 PIE scientists presenting LTER research to a total of 60 teachers. Four LTER scientists (including students) shared their research on striped bass in an “Ocean Science Education Institute” for 50 youth and adults. These scientists also assisted a team of educators in developing and piloting curriculum based on LTER bass research. The Ocean Science Institute is a component of the Gulf of Maine Institute, which receives additional support from the Massachusetts Environmental Trust, NSF via the Center for Ocean Science Educational Excellence (COSEE), Mass Audubon and GE via the Corporate Wetlands Restoration Partnership. Duff has worked to develop a partnership with the Harvard Forest LTER by enrolling teachers from the PIE region in the HFR Schoolyard study of “Bud’s Leaves and Global Warming.” To help the greater community learn more about LTER science we have written and published articles about LTER research in Mass Audubon’s “Connections” magazine.

It is particularly challenging to maintain a strong Schoolyard Program given the vagaries and fluctuations in funding. During years of “extra” support the SMS program was able to serve a greater proportion of urban students, including those from the lower income Dorchester and East Boston neighborhoods. While during baseline funding, the SMS “reach” drops from about 1500 students to about 1000.

**Undergraduates and REU’s:** Each summer the LTER and associated projects support 2 or more students in the NSF Research Experience for Undergraduates program. Each student works closely with a principal investigator and either post-doc or research assistant. Students typically help out with the various field activities that are occurring at Plum Island (thereby gaining a broad research experience), plus they conduct their own independent research projects. Each student is required to prepare a poster and short manuscript describing their research project. Students typically participate in the Marine Biological Laboratory Annual Scientific Meeting and present their research reports or they present their reports at the Audubon facility at Joppa Flats in Newburyport. See Appendix I for list of students and project titles.

MBL offers an undergraduate Semester in Ecosystems Science (full 15 credits) annually. Over the past 4 years, PIE investigators have supervised numerous students with independent projects that are related to our aquatic research at PIE (see Appendix I).

Over the past several years, 81 undergraduates have been affiliated with the PIE LTER

**Graduate Students, Post-docs and Research Interns:** Perhaps our most effective means of education is through graduate student training, post-doctoral fellowships and research assistant internships. Over the past 3 years PIE has supported 35 graduate students, 27 of whom were directly affiliated with PIE. We have supported 8 Post-docs at the Marine Biological Laboratory and collaborated with 8 others from MIT. We typically offer 2 research assistant fellowships (RAF) to recent college graduates prior to beginning graduate school. In the past several years we have supported 8 RAFs, most of whom have gone on to graduate school in ECOSYSTEM science (see appendix I).

**Science Writers:** Each summer the Marine Biological Laboratory supports a course for professional science writers (TV, newspaper, journal, etc). These people play a critical role in our society, as they try to inform the public of the excitement and concepts that scientists work on. An informed public is the cornerstone of a democratic society. Public support for science depends on effective channels of communication between science and the general public. Over the past several years, many of these writers have been exposed to ecosystem research looking at

N loading from land to coastal systems. This past summer a writer initiated a story on the “low water” situation in the Ipswich River.

## **OUTREACH**

Our goal is to communicate our findings to individuals, organizations (NGOs), and government agencies that will use our research results to better manage local and regional coastal resources. We support four types of activities: communicating what we do, advising NGOs and government agencies on issues of concern to them, collaborating with NGOs and government agencies on environmental research, and applying our scientific knowledge through public service. We have established communications and partnerships on four major issues: intertidal marshes, coastal eutrophication, watershed resource management and fisheries (Table EO-1).

Our primary outreach effort is communicating with the public, NGOs, government agencies, and other scientists. We reach the public through a variety of mechanisms including talks (e.g., Deegan at the Newburyport and Ipswich Rotary Clubs), newsletters (e.g., *Earthkeepers* article on eutrophication), magazines (e.g., *MBL Catalyst* highlighted Hopkinson’s involvement in promoting ecosystems services-based management), brochures (e.g., the PIE LTER brochure), and community-wide open houses (e.g., at our Marshview Field Station in Newbury, MA). In addition, we have developed ‘Adopt-a-bass’ and ‘Adopt-a-herring’ programs and web pages (<http://www.Ipswich-riverherring.com/index.html>) to engage the public in our research. To reach our scientific peers we communicate with journal publications (listed as an Appendix to this report) and presentations at national and international scientific society meetings.

We also seek opportunities to advise various NGO and government agencies on issues where we have developed knowledge resulting from LTER research. Wollheim and Hopkinson have attended numerous workshops sponsored by the Ipswich River Watershed Association dealing with low flow issues in the Ipswich River and we also serve on their Technical Advisory Council. Others of us have been involved in workshops with Mass CZM, Region 1 EPA, NMFS, and USFWS discussing issues such as marsh dieback, sea level rise, marsh invasives, and eutrophication. Jim Morris and Linda Deegan have advised US Senators and Representatives and their staffers (SC and Mass) on issues of sea level rise and coastal eutrophication. Morris has also discussed the ramifications of sea level rise on coastal systems through activities organized by the Heinz Center.

PIE LTER has established several research collaborations with several NGOs and government agencies. Mather has been working with several state and federal agencies as well as NGOs in studying striped bass and the recovery of river herring in the Plum Island system. Wollheim and Hopkinson have collaborated with the Ipswich River watershed association in monitoring river health. Several of us worked with a diverse group of NGO’s and state and local agency people to develop a proposal to wisely manage growth in the Ipswich River watershed. Several of us have also helped Mass DEP and the PRNWR in restoring historically impounded salt marshes in the system. And several of us have also been working with NOAA and CZM in developing a digital elevation model and map of marsh plant species distribution through remote sensing (LIDAR and multispectral). Our annual ‘All Scientists Meeting’ has been an excellent way to get our information to our partner organizations and government agencies.

We use our scientific knowledge in providing several public services. Linda Deegan serves on the Falmouth Conservation Commission. Anne Giblin organized and spearheaded the construction of a “science-theme playground” in Falmouth. Jane Tucker serves on the Falmouth

Coastal Resources Working Group. Several of us have advised students and served as judges for school science fairs (including Garritt, Tucker, Hopkinson, Giblin, Morris).

Finally, the PIE LTER has an extensive outreach arm through the activities of PI Robert Buchsbaum, who through the Audubon Society, interacts directly with the local and state management community. He is a member of the Great Marsh Salt Marsh Restoration Team, a committee organized by the Massachusetts Wetlands Restoration Program under the Massachusetts Office of Coastal Zone Management. Participants include staff from a variety of state and federal agencies: MA CZM, NOAA, USFWS (Parker River National Wildlife Refuge – PRNWR)), the EPA’s Massachusetts Bays Program, Wells National Estuarine Research Reserve, other nonprofits, and local governments. He provides updates to this committee about LTER activities and opportunities for collaboration. He is also an active member of the Gulf of Maine Council on the Marine Environment Habitat Monitoring Subcommittee. This committee has focused on monitoring salt marsh in the Gulf of Maine region. Buchsbaum has brought to the attention of this committee the work at the LTER, our network of SET tables, our marsh vegetation transect work, and our regular monitoring of water column. He has been on the organizing committee of two symposia examining the extent and cause of this phenomenon in New England. PIE has not experienced vegetation dieback to any unusual extent, but it is instructive to those in other parts of New England to relate our observations to theirs. He has also consulted with staff from the Massachusetts Wetlands Restoration Program about salt marsh haying, worked with the PRNWR and 8 Towns and the Bay Organization to develop a proposal to study the spread of *Phragmites australis* and discussed mercury contamination in salt marsh sparrows at the PRNWR and advised the Refuge on experimental design.

**Table EO-1. PIE LTER outreach activities and target audiences**

<b>Societal Issue</b>	<b>Civic Organizations, NGOs and Local Agencies</b>	<b>Massachusetts State Agencies</b>	<b>Federal Agencies</b>
<p><b>Sea Level Rise</b></p> <p><b>Wetland Restoration</b></p> <p><b>Wetland Survival</b></p>	<p>Mass Audubon Society</p> <p>Merrimack Valley Planning Commission</p> <p>Essex County</p> <p>Greenbelt Association (ECGA)</p> <p>Donnelly Foundation</p> <p>Nature Conservancy</p> <p>Heinz Center</p> <p>8 Towns and the Bay</p>	<p>Dept of Environmental Protection (DEP)</p> <p>Coastal Zone Management (CZM)</p> <p>Dept of Fish and Game</p> <p>Mass Geographic Information System (Mass GIS)</p> <p>Wetlands Restoration Program</p> <p>Mass Dept of Conservation and Recreation (DCR)</p>	<p>NRCS – Westford Service Center</p> <p>USFWS</p> <p>National Wetlands Inventory (NWI)</p> <p>Parker River National Wildlife Refuge</p> <p>USEPA - Atlantic Ecology Division (AED)</p>
<p><b>Sewage Effluent</b></p> <p><b>Discharge</b></p> <p><b>EUTROPHICATION</b></p>	<p>Ipswich River Watershed Association (IRWA)</p> <p>Parker River Clean Water Association (PRCWA)</p> <p>Island Futures Group</p> <p>Towns of Ipswich, Rowley, Newburyport</p>	<p>DEP</p> <p>DCR</p> <p>Water Resources Commission</p> <p>Mass Bays Program</p> <p>Division of Marine Fisheries (DMF)</p>	<p>USEPA – Atlantic Ecology Division (AED)</p> <p>Congressional Staffs, eg., Delahunt</p>
<p><b>Low River Flow</b></p> <p><b>River Restoration, Dam Removal and Beavers</b></p> <p><b>Land Use Change and “Smart Growth”</b></p>	<p>IRWA</p> <p>PRCWA</p> <p>Horizon Foundation</p> <p>Essex County Community Foundation</p> <p>Audubon Society</p> <p>ECGA</p> <p>Nature Conservancy</p> <p>Town of Ipswich</p>	<p>EOEA</p> <p>DEP</p> <p>DCR</p> <p>Mass GIS</p> <p>Water Resources Commission</p>	<p>USGS</p> <p>USEPA – AED</p> <p>NRCS</p>

## SITE MANAGEMENT

Considerable effort goes into maintaining open channels of communication and maximizing the input of all participants in the Plum Island Ecosystems LTER. Charles Hopkinson provides overall direction, management and coordination. Hopkinson has served in this capacity from the beginning of the LTER and previously with the LMER. Research direction, strategic scheduling of major initiatives and budgetary matters are discussed collegially amongst all PIs and decisions reached by consensus.

The Ecosystems Center at the Marine Biological Laboratory is the “home” of the PIE LTER. Six of the 11 PIs work at the Ecosystems Center. PIs and other staff at MBL meet once or twice a month (except during the summer field season) for presentation of results, information discussion and planning sessions. Summaries of these meetings are distributed by e-mail to all personnel. We hold an intensive 2-day workshop of all researchers each spring to synthesize results across programmatic areas and to plan research and/or educational activities for the coming year. Communication within PIE LTER is very high and pretty much assured as 6 of the 11 PIs have offices within 10 m of each other and Vörösmarty, Wollheim and Buchsbaum regularly visit MBL and vice versa. All the post-docs and research assistants supported on the LTER are housed in the same building. Hopkinson and Peterson are jointly funded with Vörösmarty and Wollheim on a separate project and Hopkinson has and is jointly funded with Morris, Pontius, Wollheim and Vörösmarty on additional separate projects related to the LTER. Having LTER leadership involved in most of the related, separately funded projects further integrates scientists outside MBL, which contributes to LTER cohesiveness.

Research in each programmatic area is directed by one of the principal investigators.

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

Each programmatic area typically consists of 2 to 5 other principal investigators, plus post-docs, research assistants, and graduate students. These groups get together at regular intervals that vary from year to year as research focus is moved from one programmatic area to another. It is within these groups that most collaboration with non-LTER scientists occurs. We have also established working groups for discussing meteorological/atmospheric deposition issues, Data and Information Management, and Long-Term Experiments.

The PIE LTER makes use of two field stations: Marshview Farms and the Rowley House. Marshview Farms was purchased by MBL about 5 years ago in support of LTER and related MBL research. Deegan is lead PI on a facilities planning grant from NSF, which we have used to determine our (and local community) field station needs, and to hire an architect to provide us with building plans that would enable us to meet expected needs. The estimated cost of Marshview expansion and renovation is about \$7M with an additional \$1M endowment fund to

support long-term operation and maintenance. We are now working with the MBL Development Office to raise funds.

The Rowley House is rented from the Essex County Greenbelt Association, a local land preservation organization. While this facility is small it provides excellent logistical support via its walking proximity to many of our marsh research sites, its proximity to a railroad station to Boston and its waterfront dock space. The Rowley House is typically used by “expedition mode” scientists (1-4 or 5 day visits), while Marshview Farms is used by those staying for extended periods (e.g., the entire summer). To date, facility occupancy is arranged via a web signup protocol: first come - first serve. To date we have not had scheduling issues of any concern, with everyone being accommodated pretty much as desired. There are no field station charges – to LTER or non-LTER scientist users. There are no field station “managers”. PIs (i.e., Deegan and Hopkinson) sometimes have to remind visitors of the “scout” motto to insure facilities remain comfortable and functional. We expect that a new “model” will be required once Marshview Farms is renovated to house 24 people (living and research space) and have small workshop and meeting facilities.

## LITERATURE CITED

- Acinas SG, Klepac-Ceraj V, Hunt DE, Pharino C, Ceraj I, Distel DL, Polz MF (2004) Fine-scale phylogenetic architecture of a complex bacterial community. *Nature* 430:551-554
- Aller, R. C. 1998. Mobile Deltaic and Continental Shelf Muds as Suboxic, Fluidized Bed Reactors. *Mar. Chem.* 61:143-155.
- Bahr M, Crump BC, Klepac-Ceraj V, Teske A, Sogin ML, Hobbie JE (2005) Molecular characterization of sulfate-reducing bacteria in a New England salt marsh. *Environmental Microbiology* 7:1175-1185.
- Battin, T. J., L. Kaplan, S. Findlay, C. Hopkinson, E. Marti, A. Packman, J. D. Newbold, F. Sabater. 2007. Biophysical controls on organic carbon fluxes in fluvial networks. *Nature Geoscience* (in review following revision).
- Beaulieu, J. and 30 others including B. Peterson. In prep. Nitrous oxide emissions from headwater streams. To be submitted to *Science*
- Bernhard AE, Tucker J, Giblin AE, Stahl DA. 2007. Functionally distinct communities of ammonia-oxidizing bacteria along an estuarine salinity gradient. *Environmental Microbiology* 9:1439-1447
- Bernhard, Anne E., Thomas Donn, Anne E. Giblin, and David A. Stahl. 2005. Loss of Diversity of Ammonia-Oxidizing Bacteria Correlates with Increasing Salinity in an Estuary System. *Environmental Microbiology* 7: 1289-1297.
- Blair, N. E., Leithold, S. Ford, K. Peeler, J. Holmes, and D. Perkey. 2003. The Persistence of Memory: The Fate of Ancient Sedimentary Carbon in a Modern Sedimentary System. *Geochim. Cosmochim. Acta* 67:63-73.
- Chen, C., Liu, H., and Beardsley, R. C. 2003. An unstructured grid, finite-volume, three-dimensional, primitive equations ocean model: application to coastal ocean and estuaries. *Journal of Atmospheric and Oceanic Technology* 20, 159-186.
- Claessens, L., C. Hopkinson, E. Rastetter, and J. Vallino. 2006. Evaluating the effect of historical changes in land use and climate on the water budget of the Ipswich River Basin, Massachusetts, USA. *Water Resources Res.* 42: WO3246, doi:10.1029/2005WR004131, 2006.
- Coffin, R. B., B. Fry, B. J. Peterson and R. T. Wright. 1989. Carbon isotope compositions of estuarine bacteria. *Limnol. Oceanogr.* 34:1305-1310.
- Coffin, R. B., R. T. Wright 1991. Short-term variations of microbial populations in the Parker River Estuary. Unpublished ms.
- Crossett, K., T. Culliton, P. Wiely and T. Goodspeed. 2004. Population trends along the coastal United States: 1980-2008. Coastal Trends Report Series. NOAA Special Project Office, Silver Springs, MD.
- Crump BC, Hobbie JE. 2005. Synchrony and seasonality of bacterioplankton communities in two temperate rivers. *Limnology And Oceanography* 50:1718-1729
- Crump BC, Hopkinson CS, Sogin ML, Hobbie JE. 2004. Microbial biogeography along an estuarine salinity gradient: Combined influences of bacterial growth and residence time. *Applied and Environmental Microbiology* 70:1494-1505
- Deegan, L. A. and R. H. Garritt. 1997. Evidence for spatial variability in estuarine food webs. *Marine Ecology Progress Series* 147:31-47.
- Deegan, L. A., and R. H. Garritt. 1997. Evidence for Spatial Variability in Estuarine Food Webs. *Marine Ecology Progress Series* 147:31-47.

- Deegan, L., J. Bowen, D. Drake, J. Fleeger, C. Friedrichs, K. Galvin, J. Hobbie, C. Hopkinson, S. Johnson, M. Johnson, L. LeMay, E. Miller, B. Peterson, C. Picard, S. Sheldon, M. Sutherland, J. Vallino, and S. Warren. 2007. Susceptibility of salt marshes to nutrient enrichment and predator removal. *Ecol. Appl.* 17: S42-S63.
- Deegan, L.A. J. L. Bowen, D. Drake, J. W. Fleeger, C. T. Friedrichs, K. A. Galván, J. E. Hobbie, C. Hopkinson, J. M. Johnson, D. S. Johnson, L. E. Lemay, E. Miller, B. J. Peterson, C. Picard, S. Sheldon, J. Vallino, R. S. Warren. 2007. Susceptibility of salt marshes to nutrient enrichment and predator removal. Special Issue "Nutrient Enrichment Of Estuarine And Coastal Marine Environments" (Mike Kennish, Special Issue Editor). *Ecological Applications* 17(5):S42-S63.
- Dewar, R. 2003. Information theory explanation of the fluctuation theorem, maximum entropy production and self-organized criticality in non-equilibrium stationary states. *Journal of Physics A: Mathematical and General* 36, 631-641.
- Dewar, R.C. 2005. Maximum entropy production and the fluctuation theorem. *Journal of Physics A: Mathematical and General* 38, (21) L371-L381, doi: 10.1088/0305-4470/38/21/L01.
- Drake, D., L.A. Deegan, L.A. Harris, E.E. Miller, B.J. Peterson, and R.S. Warren. In Press. 2007. Plant N dynamics in fertilized and natural New England saltmarshes: A paired  $\square^{15}\text{N}$  tracer study. *Marine Ecology Progress Series*.
- Drake, D.C., B.J. Peterson, L.A. Deegan, L.A. Harris, E.E. Miller, and R.S. Warren. 2007. Plant N Dynamics in Fertilized and Natural New England Salt Marshes; A Paired  $^{15}\text{N}$  Tracer Study. *Marine Ecology Progress Series*, in press.
- Driscoll, C., D. Whitall, J. Aber, E. Boyer, M. Castro, C. Cronan, C. Goodale, P. Groffman, C. Hopkinson, K. Lambert, G. Lawrence, and S. Ollinger. 2003. Nitrogen pollution in the northeastern United States: Sources, effects and management options. *BioScience* 53:357-374.
- Driscoll, C., D. Whitall, J. Aber, E. Boyer, M. Castro, C. Cronan, C. Goodale, P. Groffman, K. Lambert, G. Lawrence, C. Hopkinson and S. Ollinger. 2002. Nitrogen Pollution: from the sources to the sea. *Science Links - Hubbard Brook Research Foundation*, Hanover, NH. 4 p.
- Fagherazzi, S., R. Torres, C. Hopkinson and D. van Proosdij. 2005. Salt marsh geomorphology: physical and ecological effects on landform. *EOS - AGU Transactions* 8: 57-58
- Farber, S., R. Costanza, D. Childers, J. Erikson, K. Gross, M. Grove, C. Hopkinson, J. Kahn, S. Pincetl, A. Troy, P. Warren, and M. Wilson. 2006. Linking ecology and economics for ecosystem management. *BioScience* 56: 117-129.
- Fedorko, E. J., R. G. Pontius, S. P. Aldrich, L. Claessens, C. Hopkinson, and W. M. Wollheim. 2005. Spatial distribution of land type in regression models of pollutant loading. *Journal of Spatial Hydrology* 5:61-80.
- Ferry, K. H. 2003. Factors driving distribution of migratory striped bass across Massachusetts's estuaries: predator-prey interactions and implications for multi-species management. MS Thesis, University of Massachusetts, Amherst. 126 pp.
- Filoso, S., J. J. Vallino, C. Hopkinson, and E. B. Rastetter. 2004. Modeling nitrogen transport in the Ipswich R. basin, Massachusetts, using HSPF: Present conditions and future scenarios. *Journal of the American Water Resources Association* 40:1365-1384.
- Gardner, L.R. in prep. A method for estimating seepage from marsh soils using rainfall and well records.

- Giblin, A. E., N. Weston, G. Banta, C. S. Hopkinson, and J. Tucker. The Effect of Salinity on Nitrogen Dynamics in Estuarine Sediments. submitted
- Giblin, A.E., N. Weston, G.T. Banta, J. Tucker, C.S. Hopkinson. The effect of salinity on nitrogen losses from an oligohaline estuarine sediment. Submitted *Estuaries and Coasts*.
- Haas, H., C. Freeman, L. A. Deegan, B. Fry, E. Gaines, J. Logan, R. S. Warren. In prep. Examining mummichog growth and movement: Are some individuals making intra-season migrations to optimize growth? *Journal of Experimental Marine Biology and Ecology*.
- Hayden, B., and N. Hayden. 2003. Decadal and Century-Long Changes in Storminess at LTER Sites. Pages 262-285 in D. Greenland, D. Goodin, and R. Smith, editors. *Climate Variability and Ecosystem Response at LTER Sites*. Oxford University Press.
- Hedges, J., R. Keil, and R. Benner. 1997. What Happens to Terrestrial Organic Matter in the Ocean? *Org. Geochem* 27:195-212.
- Holmes, R. M., B. J. Peterson, L. Deegan, J. Hughes, and B. Fry. 2000. Nitrogen Biogeochemistry in the Oligohaline Zone of a New England Estuary. *Ecology* 81:416-432.
- Hopkinson, C. and A. Giblin. 2007. Salt marsh N Cycling. In- R. Capone, D. Bronk, M. Mulholland and E. Carpenter (eds), *Nitrogen in the Marine Environment – 2nd Edition*. Elsevier Publ. (in press).
- Hopkinson, C. and E. Smith. 2004. Estuarine respiration, pages 122-146. In- P. del Giorgio and P.J. leB. Williams. *Respiration of Aquatic Ecosystems of the World*. Academic Press, NY. 328 p.
- Hughes, J. E., L. A. Deegan, B. J. Peterson, R. M. Holmes, and B. Fry. 2000. Nitrogen Flow through the Flood Web in the Oligohaline Zone of a New England Estuary. *Ecology* 81:433-452.
- Ip, J.T.C., Lynch, D.R., and Friedrichs, C.T. 1998. Simulation of estuarine flooding and dewatering with application to Great Bay, New Hampshire. *Estuarine, Coastal Shelf Sci.* 47, 119-141.
- Kirkby, R., Claessens, L., Hopkinson, Jr. C., Rastetter, E., and Vallino, J. 2000. Modeling the effects of land-use change on nitrogen biogeochemistry in the Ipswich watershed, Massachusetts. *Biol. Bull.* 199, (2) 218-219.
- Klepac-Ceraj V, Bahr M, Crump BC, Teske AP, Hobbie JE, Polz MF (2004) High overall diversity and dominance of microdiverse relationships in salt marsh sulphate-reducing bacteria. *Environmental Microbiology* 6:686-698
- Könneke M., Bernhard, A. E., de la Torre, J. R., Walker, C. B., Waterbury, J. B. and Stahl, D. A. (2005) Isolation of an autotrophic ammonia-oxidizing marine archaeon. *Nature* 437: 543-546.
- Logan, J., H. Haas, L. A. Deegan, and E. Gaines. 2006. Turnover rates of nitrogen stable isotopes in the salt marsh mummichog, *Fundulus heteroclitus*, following a laboratory diet switch. *Oecologia* 147:391-395.
- Lorenz, R. 2003. COMPUTATIONAL MATHEMATICS: Full Steam Ahead-Probably. *Science* 299, (5608) 837-838.
- McKee, B. 2003. Riomar: The Transport, Transformation, and Fate of Carbon in River-Dominated Ocean Margins. Report of the Riomar Workshop. Tulane University, New Orleans, LA.

- Morris, J.T. 2006. Competition among marsh macrophytes by means of geomorphological displacement in the intertidal zone. *Estuarine and Coastal Shelf Science* 69:395-402.
- Morris, J.T. 2007a. Ecological engineering in intertidal saltmarshes. *Hydrobiologia* 577:161-168.
- Morris, J.T. 2007b. Effects of rate of sea level rise and tidal amplitude on relative marsh elevation and sediment organic matter accumulation. Abstract of invited talk given at the 10th International Symposium on Biogeochemistry of Wetlands, Annapolis, MD. April, 2007
- Morris, J.T., P.V. Sundareshwar, C.T. Nietch, B. Kjerfve, D.R. Cahoon. 2002. Responses of coastal wetlands to rising sea level. *Ecology* 83:2869-2877.
- Mulholland, P. J. and 30 others including B. Peterson. In review. Denitrification and nitrate removal by stream networks: effects of agriculture and urbanization. *Nature* (in review).
- Mulholland, P. J., and a. others. In Review. Excess nitrate from agricultural and urban areas reduces denitrification efficiency in streams. *Nature*.
- NRC (Howarth, R. W., D. Anderson, T. Church, H. Greening, C. Hopkinson, W. Huber, N. Marcus, R. Naiman, K. Segerson, A. Sharpley and W. Wiseman - Committee on the Causes and Management of Coastal Eutrophication) 2000. Clean Coastal Waters – Understanding and reducing the effects of nutrient pollution. Ocean Studies Board and Water Science and Technology Board, Commission on Geosciences, Environment, and Resources, National Research Council. National Academy of Sciences, Washington, D.C. 405 p.
- Pellerin, B. A., W. M. Wollheim, C. S. Hopkinson, W. H. McDowell, M. R. Williams, C. J. Vorosmarty, and M. L. Daley. 2004. Role of wetlands and developed land use on dissolved organic nitrogen concentration and DON/TDN in northeastern U.S. rivers and streams. *Limnology and Oceanography* 49:910-918.
- Pellerin, B. A., W. M. Wollheim, X. Feng, C. J. Vorosmarty, and A. M. Faiia. In Press. The role of surface runoff in urban stormflow generation: Inferences from chemical and isotopic hydrograph separation. *Hydrological Processes* In Press.
- Peterson, B. J., B. Fry, M. Hullar, S. Saupé and R. Wright. 1994. The distribution and stable carbon isotopic composition of dissolved organic carbon in estuaries. *Estuaries* 17(1B):111-121.
- Pontius, R. G., A. Agrawal, and D. Huffaker. 2003. Estimating the uncertainty of land-cover extrapolations while constructing a raster map from tabular data. *Journal of Geographical Systems* 5:253-273.
- Pontius, R. G., A. J. Versluis, and N. R. Malizia. 2006. Visualizing certainty of extrapolations from models of land change. *Landscape Ecology* 21:1151-1166.
- Pontius, R. G., D. Huffaker, and K. Denman. 2004. Useful techniques of validation for spatially explicit land-change models. *Ecological Modeling* 179.
- Raymond, P., and C. Hopkinson. 2003. Ecosystem modulation of dissolved carbon age in a temperate marsh-dominated estuary. *Ecosystems* 6:694-705.
- Schneider, L., and R. G. Pontius. 2001. Modeling Land-Use Change in the Ipswich Watershed, Massachusetts, USA. *Agriculture, Ecosystems & Environment* 85:83-94.
- Thompson JR, Pacocha S, Pharino C, Klepac-Ceraj V, Hunt DE, Benoit J, Sarma-Rupavtarm R, Distel DL, Polz MF (2005) Genotypic diversity within a natural coastal bacterioplankton population. *Science* 307:1311-1313

- Tobias, C. R., M. Cieri, B. J. Peterson, L. A. Deegan, J. Vallino, and J. Hughes. 2003*b*. Processing Watershed-Derived Nitrogen in a Well-Flushed New England Estuary. *Limnol. Oceanogr.* 48:1766-1778.
- Tobias, C., A. E. Giblin, J. McClelland, J. Tucker, and B. Peterson. 2003*a*. Sediment Din Fluxes and Preferential Recycling of Benthic Microalgal Nitrogen in Shallow Macrotidal Estuary. *Marine Ecological Progress Series* 257:25-36.
- Torres, R., S. Fagherazzi, D. van Proosdij and C. Hopkinson. 2006. Salt marsh geomorphology: physical and ecological effects on landform. *Est. Coastal Shelf Sci.* 69: 309-310.
- Valentine, V., C.S. Hopkinson, Jr., Millette, T.L., C.D. Hayward, C. Lawrence, and J. Goldstein. Formation of pools in marshes of the Plum Island Sound estuary.
- Vallino, J. J., and C. S. Hopkinson. 1998. Estimation of Dispersion and Characteristic Mixing Times in Plum Island Sound Estuary. *Estuarine, Coastal and Shelf Science* 46:333-350.
- Vallino, J.J. 2003. Modeling Microbial Consortia as Distributed Metabolic Networks. *Biol Bull* 204, (2) 174-179.
- Walter, J. F., A. S. Overton, K. F. Ferry, and M. E. Mather. 2003. Atlantic coast feeding habits of striped bass: a synthesis supporting a coast-wide understanding of trophic biology. *Fisheries Management and Ecology* 10:1-13.
- Werner, E. and S. Peacor. 2003. A review of trait-mediated indirect interactions in ecological communities. *Ecology* 84:1083-1100.
- Werner, E. E., S. D. Peacor. 2003. A review of trait-mediated indirect interactions in ecological communities. *Ecology* 84:1083-1100.
- Weston, N.B., A.E. Giblin, G.T. Banta, C.S. Hopkinson, and J. Tucker. The effects of varying salinity on ammonium exchange in estuarine sediments of the Parker Rier, Massachusetts. Submitted. *Estuaries*.
- Williams, M., C. H. Hopkinson, E. B. Rastetter, and J. Vallino. 2004. N budgets and aquatic uptake in the Ipswich R. basin, northeastern Massachusetts. *Water Resource Research* 40:W11201.
- Williams, M., C. Hopkinson, E. Rastetter, J. Vallino, and L. Claessens. 2005. Relationships of land use and stream solute concentrations in the Ipswich River basin, northeastern Massachusetts. *Water Air and Soil Pollution* 161:55-74.
- Wollheim, W. M., B. A. Pellerin, C. J. Vorosmarty, and C. S. Hopkinson. 2004. Nitrogen removal by the river network of the 400 km<sup>2</sup> Ipswich River watershed, MA, USA. *in* AGU Spring Meeting, Montreal, Canada.
- Wollheim, W. M., B. A. Pellerin, C. J. Vorosmarty, and C. S. Hopkinson. 2005. N retention in urbanizing headwater catchments. *Ecosystems* 8:871-884.
- Wollheim, W. M., B. J. Peterson, C. J. Vorosmarty, C. Hopkinson, and S. A. Thomas. In Preparation. Dynamics of N removal over annual time scales in a suburban river network.
- Wollheim, W. M., C. J. Vorosmarty, A. F. Bouwman, P. A. Green, J. Harrison, E. Linder, B. J. Peterson, P. A. Green, S. Seitzinger, and J. P. M. Syvitski. In Review. Global N removal by freshwater aquatic systems: a spatially distributed, within-basin approach. *Global Biogeochemical Cycles*.
- Wollheim, W. M., C. J. Vorosmarty, B. J. Peterson, S. P. Seitzinger, and C. S. Hopkinson. 2006. Relationship between river size and nutrient removal *Geophysical Research Letters* 33:doi:10.1029/2006GL025845.
- Wright, R. T., R. B. Coffin, and M. E. Lebo. 1987. Dynamics of planktonic bacteria and heterotrophic microflagellates in the Parker estuary, northern Massachusetts. *Cont. Shelf Res.* 7: 1383-1397.

- Zarriello, P. J. and Ries III, K. G. 2000 A precipitation-runoff model for analysis of the effects of water withdrawals on streamflow, Ipswich River basin, Massachusetts. Water-Resources Investigation Report 00-4029, U.S. Geological Survey, Northborough, MA, 99 pp.
- Zheng,L., Chen,C., and Liu,H. 2003. A modeling study of the Satilla River Estuary, Georgia. I: flooding-drying process and water exchange over the salt marsh-estuary-shelf complex. *Estuaries* 26, (3) 651-669.