LTER: Linking Pelagic Community Structure with Ecosystem Dynamics and Production Regimes on the Changing Northeast US Shelf

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PROJECT SUMMARY

Overview:

The northwest Atlantic, renowned for its fisheries, is experiencing faster-than-average warming and other climate-related impacts. The PIs propose a Northeast US Shelf (NES) Long-Term Ecological Research (LTER) program to understand and predict how planktonic food webs change through space and time, and how those changes impact the productivity of higher trophic levels in this coastal biome. While patterns of ecosystem change over seasons to decades have already been documented in this region, the key mechanisms linking changes in the physical environment, planktonic food webs, and higher trophic levels remain poorly understood. For this reason, predictive capability is limited and management strategies are largely reactive. To address these needs, the NES-LTER strategy combines observations that provide regional-scale context, process cruises along a high gradient cross-shelf transect, high-frequency time series at inner- and outer-shelf locations, coupled biological-physical food web models, and targeted population models. The long term research plan is guided by an overarching science question: How is climate change impacting the pelagic NES ecosystem and, in particular, affecting the relationship between compositional (e.g., species diversity and size structure) and aggregate (e.g., rates of primary production, and transfer of energy to important forage fish species) variability? By capitalizing on high levels of seasonal and interannual variability in the NES, the PIs will study short-term responses to climate-related variables to a) characterize low and high export food webs, b) understand the linkages and transfer of energy from the phytoplankton to pelagic fish, and c) identify the mechanisms that underlie shifts between high and low export communities. Ultimately, mechanistic knowledge will be scaled up to understand and predict the impacts and feedbacks associated with decadal- to climate-scale forcing in the ecosystem.

Intellectual Merit :

In NES waters, human activities, environmental variability, and climate change intersect to have complex effects on ecosystem dynamics. There are indications that the pace of change is accelerating in this region, but the lack of a systematic approach to observe multiscale changes with sufficient detail limits understanding of the underlying causes and implications. Quantifying and understanding variability on seasonal, interannual, and decadal time scales will enable prediction of future productivity and ecosystem state. This will include assessment of the extent to which the NES ecosystem exhibits enough biodiversity to be resilient to dramatic changes in overall productivity caused by rapid environmental change. Furthermore, comparing patterns of change and their causes with other coastal regions (e.g., CCE-LTER, Palmer-LTER) that differ in physical forcing and patterns of disturbance will help uncover the underlying ecological principles that shape coastal ocean pelagic systems and their vulnerability worldwide.

Broader Impacts :

The NES provides an array of ecosystem services including energy development, shipping, recreation, and conservation; its integrity is critical to the health of the Northeast US economy. Fishing alone generates over $100 billion in annual economic activity. Endangered species that use the NES ecosystem include Atlantic salmon, the North Atlantic right whale, and the Roseate Tern. In the face of climate change, sustaining these ecosystem services and protecting endangered species will require effective and efficient management. The prospects for effective management will be enhanced by the improved understanding of ecosystem dynamics and functioning that the NES-LTER will provide. To this end, the PIs will collaborate and share data with NOAA’s Northeast Fisheries Science Center to support their efforts in multispecies, ecosystem-based management on the NES. In addition to outreach to managers, policymakers, and fishermen, the PIs propose an education plan that will provide opportunities to a broad range of learners. At the K-12 level, the PIs will develop a new LTER Schoolyard project focusing on middle school and high school curricula. They will engage K-12 faculty in a variety of ways, including professional development workshops and research experiences. Over the course of the project, research experiences will be provided to postdoctoral investigators, graduate students, and over 30 undergraduates. The PIs will also develop a far-reaching public outreach component through NOAA’s international Science-On-a-Sphere network.

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1 PROPOSED RESEARCH

1.1 Overview

We propose a Long-Term Ecological Research (LTER) project that will improve understanding of the drivers and mechanisms of change in the Northeast US Shelf (NES) ecosystem spanning the Middle Atlantic Bight (MAB) and the Gulf of Maine (GoM) (Fig. 1).

The NES ecosystem is a large portion of the NW Atlantic Shelves Province and is in a coastal biome. The waters over the NES provide an array of ecosystem services including fishing, energy development, shipping, waste disposal, recreation, and conservation. A productive NES ecosystem is critical to the health of the Northeast US economy. Fishing alone generates well over $100 billion in annual economic activity (Hoagland et al. 2005). Iconic endangered species that use the NES ecosystem include Atlantic salmon, the North Atlantic right whale, and the Roseate Tern.

These ecosystem services (which are typical of temperate shelf ecosystems) are largely fueled by a food web based on a diverse set of single-celled planktonic primary producers that support herbivorous zooplankton and many higher-order consumers, including fish, birds, and mammals (including humans). These pelagic food webs are complex, containing relatively long food chains compared with terrestrial webs despite lower levels of primary productivity (Cohen 1994). McGarvey et al. (2016) have recently attributed this finding to efficient ectothermic metabolisms of the lower animal trophic levels in pelagic webs and the relatively smaller pelagic animal body sizes that permit more rapid trophic energy transfer.

The NES ecosystem, like other productive temperate shelf ecosystems, is characterized by strong seasonality along with high levels of variability in physical forcing at timescales from days to decades. This forcing produces a complex and highly dynamic ecosystem, with key biological and physical characteristics (including species composition, primary production, and temperature) changing

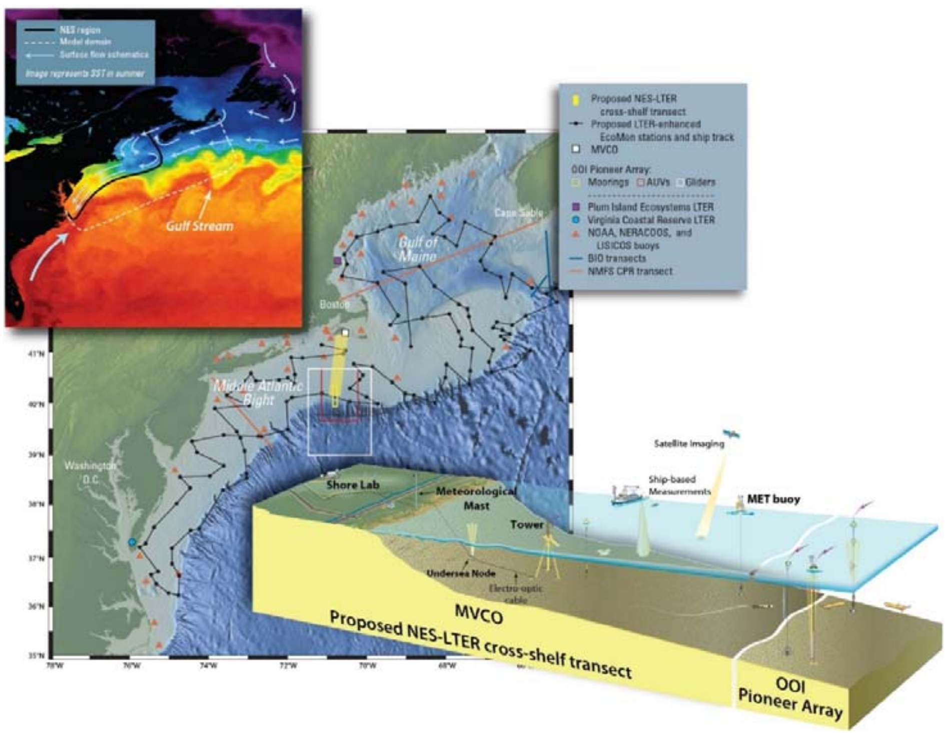

Fig. 1. The greatest focus of the proposed NES-LTER is on a cross-shelf transect from MVCO to the OOI Pioneer Array (foreground). However, quarterly EcoMon surveys (central map shows example cruise track) and biannual trawl surveys by NOAA colleagues, along with LTER-specific enhancements to these cruises, will provide select information at broad spatial scales and a greater contextual understanding of changes occurring in the NES ecosystem. Additional observations will come from regional observing system components (e.g., NOAA buoys; see Table 1). The proposed multi-scale modeling effort will address the impacts of high latitude processes and basin-scale forcing in this highly advective system by encompassing a domain that extends beyond NES boundaries (top left, with characteristic SST distribution). Slopeward extent of the OOI infrastructure is not depicted in the transect.

dramatically both seasonally and at shorter timescales. While some patterns of change from seasons to decades have been documented, the processes and mechanisms linking changes in the physical environment with changes in planktonic food webs and higher trophic levels remain poorly understood. For this reason, even short-term predictive capability remains limited and management strategies are largely reactive.

Superimposed on this (stationary) variability are the long-term, but accelerating, trends that accompany anthropogenic climate change. There is growing evidence that the NES ecosystem is undergoing significant change in the physical environment as well as in the spatial and temporal distributions of organisms from plankton to top predators (e.g., Kane and Prezioso 2008; Lucey and Nye 2010; Nye et al. 2011; Greene et al. 2013; Pershing et al. 2015). These changes are already influencing ecosystem structure and biogeochemical transformations, and have socio-ecological implications for fisheries and other marine resources.

The overarching goal of the NES-LTER will be to understand and predict how planktonic food webs change through space and time in response to changes in the physical environment, and how those changes impact ecosystem productivity, particularly of higher trophic levels. Our focus will be on processes and mechanisms that structure pelagic food webs, trophic transformations, and productivity, as well as the key interactions and feedbacks that modulate relationships among them. An LTER approach is critical here for disentangling high levels of natural variation in ecosystem processes (such as primary production) that occur on timescales of days to decades from long-term trends in those same processes that are driven by anthropogenic forcing.

Ultimately, the knowledge we obtain about the way the NES ecosystem is structured and responds to change will provide a foundation for understanding and predicting climate and other impacts on ecosystem function in temperate western boundary current systems worldwide. Furthermore, comparisons across marine systems with fundamentally different physical forcing and disturbance regimes, including the NES, California Current Ecosystem, and Palmer LTER sites, will provide insights into the underlying ecological principles that shape coastal ocean pelagic systems.

1.2 Conceptual and Theoretical Framework

There are (at least) two types of variability that ecological communities exhibit in response to environmental variation: compositional and aggregate. *Compositional variability* reflects change in the relative abundance of component species; *aggregate variability* reflects changes in summary properties such as total abundance, biomass, or production. Understanding both of these aspects of community variability is critical for predicting the responses of community structure and function to physical and/or biological perturbations.

Micheli et al. (1999) organized combinations of compositional and aggregate variability into four categories (Fig. 2a). *Synchronous* communities exhibit low levels of compositional variability and high levels of aggregate variability (species abundances show large highly correlated fluctuations). Synchrony may result if all the species in a community respond in the same way to a strong abiotic driver. If instead species respond differently to the same driver, or respond to different (uncorrelated) drivers, community dynamics may be *asynchronous*, with high compositional and high aggregate variability. *Stasis* may result from strongly competitive interactions in a relatively stable environment. Species abundances in a *compensatory* community are negatively correlated because, for example, shifts in competitive superiority occur with changing environmental conditions; aggregate community properties show little variability when compensation is the dominant dynamic.

Both theoretical and empirical analyses have focused on trying to understand the food web structures and processes that favor either synchrony or compensation, as these seem to be the most prevalent dynamics in natural communities. In addition, it is important to distinguish between these two forms of community variability, and to predict how compositional and aggregate variability will respond to climate change, for effective ecosystem management (Micheli et al. 1999).

Vasseur et al. (2014) and Defriez et al. (2016) have highlighted some of the challenges associated with identifying and diagnosing the drivers of compositional and aggregate variability. Three of these challenges are particularly relevant for the NES plankton community: temporal scales, spatial scales, and

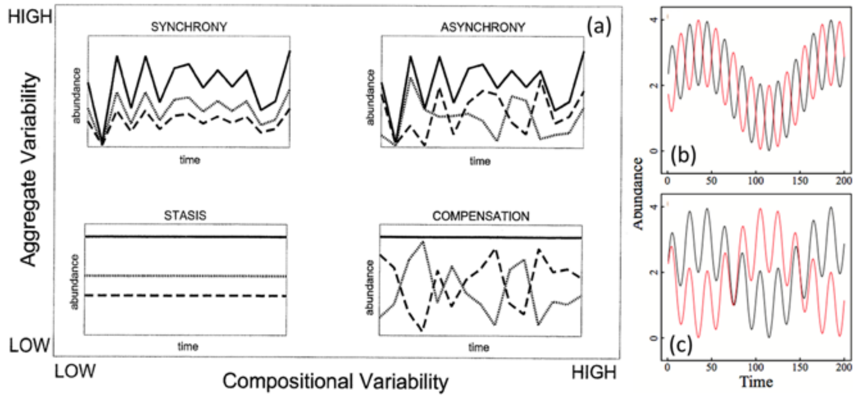

Fig. 2. (a) Communities display at least two types of variability over time: compositional variability, which results from changes in the relative representation of taxa within the community (broken lines), and aggregate variability, which results from changes in an integrated property of the community (e.g., production or standing biomass, solid lines) to which all taxa contribute. Community dynamics may appear synchronous on long timescales but compensatory on short timescales (b) or vice-versa (c). From (a) Micheli et al. (1999); (b,c) Defriez et al. (2016).

species composition. Community dynamics may appear synchronous on long time scales but compensatory on short time scales (Fig. 2b), or vice versa (Fig. 2c). A similar phenomenon occurs across spatial scales. This highlights the need for the combination of multiscale observations that we will implement as a central feature of the NES-LTER (Sec. 1.3). Finally, a lack of taxonomic resolution can also complicate the interpretation of community structure and dynamics (Lawrence and Menden-Deuer 2012). Our proposed LTER will take large steps towards finer resolution of the NES food web by applying new observing approaches across multiple trophic levels (Section 1.7, Table 2).

In Phase I, the NES-LTER project will be focused on understanding the relationship between variability in species composition and variability in aggregate properties such as production and export across a range of space and time scales in the NES ecosystem, as well as how this relationship may be influenced by climate change.

1.2.1 The changing NES ecosystem

Exactly how communities operate in any ecosystem depends on the nature of the environmental drivers and the composition of the biotic community. Both the physical drivers and the community composition are highly dynamic on the NES, and both are showing signs of rapid change.

The mean circulation through the NES is southward at ~10 cm s^{-1} and is part of a large-scale coastal current system that originates in the Arctic Ocean and ends at Cape Hatteras in the southern MAB (Chapman and Beardsley 1989). The NES is bounded offshore by a shelf break front that separates cooler, fresher shelf water from warmer, saltier, slope and Gulf Stream water (Linder and Gawarkiewicz 1998; Fratantoni and Pickart 2007). The system undergoes exceptionally large seasonal variations in water temperature and stratification (Bigelow 1933; Li et al. 2015). Shelf waters are cold (~5° C or less) and well mixed in winter due to surface heat loss and winter storms (Fig. 3). Surface heating in spring and summer and reduced storm activity leads to a seasonal thermocline that separates warm surface waters (25° C) from cold (8° C), near-bottom remnant winter water (i.e., Cold Pool, Fig. 3) (e.g., Bigelow 1933).

Living in this dynamic environment are diverse plankton communities that support variable production pathways (Fig. 3). In the GoM/MAB transition region, this is manifest at the seasonal scale by dramatic changes in community structure from a regime dominated by recurrent blooms of microplankton (mainly diatoms) beginning in fall and peaking in winter, with picophytoplankton dominating in late spring and summer (Fig. 4). This seasonal progression of bloom formation contrasts with the GoM and Georges Bank regions where the occurrence of a more quintessential spring bloom—i.e. later, more ephemeral, and more predictable than in the MAB transition region—is a nearly annual event (Friedland et al. 2015).

High-biomass blooms occur frequently nearshore and persist across the shelf but with decreasing amplitude (Yoder et al. 2002). Winter and spring microplankton blooms depend to a large extent on new nutrients that fuel net community production. These blooms are characterized by relatively short food chains and high export ratios. They are critical for providing efficient pathways of energy, mainly via large-bodied zooplankton, to upper trophic levels, including a suite of small pelagic fish species ("forage fish") and other commercially important and threatened species.

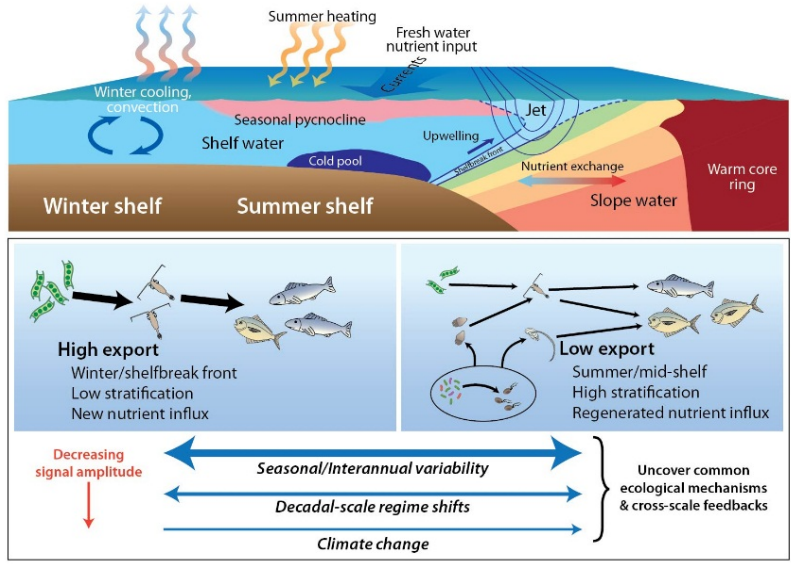

Fig. 3 Top: Conceptual diagram of physical processes across the shelf in winter and summer. Southward advection and various processes at the shelf break lead to nutrient inputs, and processes controlling stratification affect their vertical distribution. Bottom: Representative, simplified food webs of high- and low-export conditions, contrasting the relatively simple food chain of high-export with the more complex microbial loop-dominated food web of low-export conditions. Arrows at bottom indicate the range of time scales for hypothesized shifts between these food webs (and their resulting energy flow and export predictions), extending to predictions for on-going climate change.

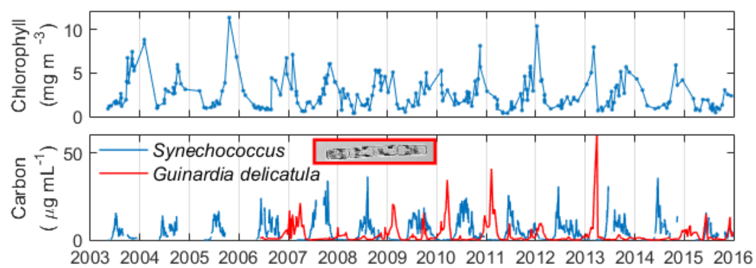

Fig. 4. On-going time series at MVCO emphasize the regular winter blooms (top) that characterize the MAB. Biomass of the dominant picophytoplankter (*Synechococcus* from automated flow cytometry) peaks in summer, while the dominant diatom (*Guinardia delicatula* from automated imaging) has its biggest blooms in winter (bottom). These preliminary records suggest the picoplankter has been increasing and the diatom decreasing over the last decade.

In contrast to blooms early in the year, summer communities on the shelf are dominated by picophytoplankton and their consumers. Although diatoms and copepods are often present, their abundance and sizes are reduced. Rates of primary production are high, though supported principally by recycled nutrient pathways in combination with favorable light and temperature conditions. The importance of regenerated nutrients in summer leads to a more complex food web that ultimately yields low export ratio conditions. These conditions may select for forage fish that are able to take advantage of the more diverse food sources in the summer (e.g., many small copepod species, appendicularians, and other gelatinous zooplankton) that tap into the microbial loop (Stoecker and Capuzzo 1990; Vargas and Madin 2004) or short-circuit it and feed directly on bacterioplankton (Fenchel 1984; Vargas and González 2004).

Nutrient concentrations are an important factor controlling pelagic food web structure in the NES. One major new nutrient source is along-shelf advection of water from higher latitudes (Fennel et al. 2006). Advective nutrient inflow varies on annual-to-decadal scales in conjunction with upstream processes that control the origin of source waters (Townsend et al. 2015). In the GoM/MAB transition (where we propose a NES-LTER focal transect across the shelf; Fig. 1), availability of those nutrients to phytoplankton is further modulated by tidal mixing and processes that control stratification and the fate of the Cold Pool. Processes associated with the shelf break front can also introduce new nutrients to shelf waters in the MAB. Although seasonality in food web structure is strong across the entire shelf, the continual influx of new nutrients at the shelf break front might lead to a food web in that zone that is characterized by high export ratio conditions throughout the year.

Climate change predictions include continuing long-term increases in water temperature (Saba et al. 2015) and stratification across the NES, which may in turn inhibit nutrient supply to the euphotic zone.

These changes may alter the timing, magnitude and duration of high-export winter blooms and increase the duration—and ecological significance—of low-export pico-phytoplankton-dominated communities (Moran et al. 2010). Phytoplankton community structure and bloom dynamics in the GoM/MAB transition zone are sensitive to temperature variability, and phenology shifts associated with warming trends have already been documented (Hunter-Cevera 2014; Hunter-Cevera et al. 2016), as they have been on a broader scale in recent years for the entire NES region (Friedland et al. 2015). Whether mediated directly by temperature or through climate-induced changes in water-column stability and nutrient regime, such changes at the phytoplankton level further affect the phenological coupling in pelagic food webs. This coupling is classically viewed as important for fisheries recruitment variability (e.g., Cushing 1990) and carbon fluxes. Moreover, changes in plankton composition can affect food web structure, altering energy transfer pathways and efficiency. Increases in smaller-sized phytoplankton, for example, are usually associated with more nutrient recycling and reduced export production. This can in turn affect the production of fisheries (Friedland et al. 2012). Indeed, there is recent evidence from an extensive time series of stable isotope values for haddock from Georges Bank (Fig. 5) that variability at the base of the food web on the NES propagates to upper trophic levels, and this variability is associated with climate indices (Llopiz et al. unpub). However, what mechanisms are driving this baseline variability, and what the specific pathways in the food web are during different regimes, has yet to be thoroughly documented.

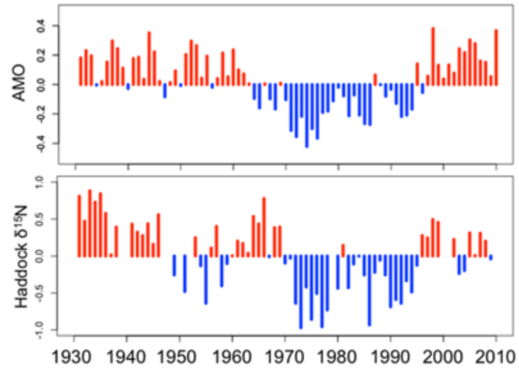

Fig. 5. Time series of the Atlantic Multidecadal Oscillation (AMO) index and $\delta^{15}N$ anomalies for haddock from Georges Bank. Evidence from other analyses (compound-specific stable isotope analysis) indicates the variability in $\delta^{15}N$ is due to changes at the base of the fish's food web (i.e. nutrients, phytoplankton) rather than changes in trophic level.

Because climate-related changes to ecosystems can be difficult to observe directly on timescales shorter than decades, we will take advantage of the fact that many of the predicted physical and ecological changes in the NES ecosystem due to climate change already occur there on seasonal and interannual timescales (e.g., annual temperature ranges from 0-20°C and annual shifts in food webs from high- to low-export). By conducting a long-term study of shelf-wide pelagic dynamics on the NES, *our goals are to (1) characterize low-export and high-export food webs, (2) identify the mechanisms that underlie shifts between low-export and high-export communities, and (3) understand the linkages and transfer of energy from the phytoplankton to pelagic forage fish.* Ultimately, we will use this knowledge of what drives seasonal and interannual dynamics to make predictions about long-term (i.e., decadal scale) climate-induced changes to the NES ecosystem.

1.3 Observational Program and Strategy

To accomplish these goals, we have designed a nested sampling strategy that spans orders of magnitude in spatial and temporal scales (Fig. 1) and encompasses (1) high-resolution, high-frequency sampling including a suite of in-water continuous measures of physical, chemical, and biological parameters, as well as monthly discrete samples, at the Martha's Vineyard Coastal Observatory (MVCO); (2) a focal transect to be sampled 4 times per year across the southern New England Shelf, between MVCO and the Ocean Observatories Initiative (OOI) Pioneer Array near the shelf break; and (3) leveraging and enhancement of NES-wide NOAA/NMFS surveys, on-going since 1977, to provide regional context and selected observations throughout the entire LTER region. The focal transect encompasses the breadth of cross-shelf processes and bisects the NES at a key transition between GoM and MAB regimes. The NOAA/NMFS surveys will allow us to place changes that occur in the focal transect area into a larger, regional perspective. In Phase I, our focus will be on pelagic observations and processes, with connections to the benthos explored in a less detailed manner through inferences from ecosystem models and some aspects of groundfish ecology. As the project matures, more comprehensive incorporation of benthic components will be encouraged through affiliated (separately funded) projects.

1.4 Additional Strengths Distinguishing the Proposed NES Site

There are several reasons the NES is an ideal site for an LTER project. First, the LTER will take advantage of several innovative observational techniques being implemented in this region that are beginning to provide new insights into changes in ecosystem structure and associated linkages. Important observational assets include MVCO, the OOI pioneer array, and the NOAA/NMFS surveys described above. Second, the project will leverage data being collated by these and other existing long-term observing systems (Table 1). Third, the mode of nutrient supply to the NES, a major driver of ecosystem dynamics, is strongly influenced by advective processes. This mode of nutrient supply is fundamentally different than wind-driven upwelling systems, such as being intensively studied in the California Current Ecosystem (CCE) and Palmer, Antarctica (PAL) LTER sites. Finally, the NES arguably has the longest historical record of both physical and biological observations on any US shelf. This record includes, for example, lightship observations extending back to the late 1800s (Shearman and Lentz 2010) and Henry Bigelow's seminal work in the early 1900s (Bigelow 1933; Bigelow and Sears 1935).

Table 1. Biological-physical-chemical data sources on the NES. AZOMP: Canadian Atlantic Zone Off-shelf Monitoring Program; AZMP: Canadian Atlantic Zone Monitoring Program; BIO-MEDS: Bedford Institute of Oceanography-Marine Environmental Data Service; CPR: Continuous Plankton Recorder; ECOHAB: Ecology and Oceanography of Harmful Algal Blooms; EcoMon: Ecological Monitoring Program, NMFS; GLOBEC: Global Ecosystem Dynamics; NERACOOS: Northeastern Regional Association of Coastal and Ocean Observing Systems; MARMAP: Marine Monitoring Assessment and Prediction, NMFS; NB: Narragansett Bay, RI; NSS: Nova Scotian Shelf; SSIP: Scotian Shelf Ichthyoplankton Program; WOD: World Ocean Database.

Data Sources	**Time Period**	**Frequency**	**Coverage**	**Key variables**
NB plankton series	1950s-present	Weekly	NB, RI	T/S, chl a, plankton
Gulf Stream Index	1954-present	Quarterly	55-75°W	Latitude of Gulf Stream
Nutrient Database	1956-present	Irregular	NES	T/S, nutrients
CPR	1961-present	Monthly, Jan-Jul	GoM, MAB	T/S, plankton
NEFSC trawl survey	1963-present	Semi-annual	NES	T/S, fish, macroinvertebrates
MARMAP	1977-1987	Bi-monthly	NES	T/S, chl, zooplankton
SSIP	1978-1982	Varied, 2-10 mo/y	NSS, GoM	nutrients, chl, zoo-/ichthyopl.
Oleander	1979 (velocity 1992)-present	Twice per week	NJ to Bermuda	T/S, velocity, nutrients, chl, plankton
Satellite SST	1982-present	Daily	Global	SST
EcoMon	1988-present	Bi-monthly	NES	T/S, zoo- & ichthyoplankton
WOD 2009	~1990-2013	Irregular	Global	T/S, nutrients
Satellite Altimetry	1992-present	Weekly	Global	Sea surface height
GLOBEC	1995-1999	Monthly, Jan-Jul	GoM	T/S, nutrients, chl, zooplank
Satellite Ocean Color	1997-present	Daily	Global	Chl, NPP, phytoplank. types
ECOHAB	1998, 2000/01	Summer	GoM	T/S, nutrient, chl
AZMP	1998-present	Monthly-seasonal	Canadian shelves	T/S, nutrients, chl, plankton
NERACOOS buoys	2001-present	Continuous	GoM	T/S, chl
MVCO	2001-present	Continuous	Coastal MA	T/S, velocity, chl, plankton
AZOMP, AR7W	2006-present	At least annually	Labrador Sea	T/S, nutrients, chl, plankton

1.5 Ecological Questions and Hypotheses

The NES-LTER strategy is focused on guiding science questions that span ecologically relevant time and space scales, ultimately requiring multi-scale, long-term observations and synthesis. Below we provide some initial guiding hypotheses but anticipate these will evolve as knowledge emerges about the processes and mechanisms that control variability at seasonal to interannual time scales. As our data records grow, we will expand our initial hypotheses and begin to characterize the impacts and feedbacks associated with decadal-scale climate-induced forcing in the ecosystem.

Our overarching question is: ***How is climate change impacting the pelagic NES ecosystem and, in particular, affecting the relationship between compositional (e.g., species diversity and size structure) and aggregate (e.g., rates of primary production, and transfer of energy to important forage fish species) variability?***

The answer to this motivating question depends (at least) on the answers to three more specific questions.

Q1: *What are the main factors controlling spatial and temporal patterns of plankton species composition and biological production?*

H1.1: Warm stratified regimes, such as those that occur naturally in summer or that could be caused by anomalously and increasingly frequent warm years, are dominated by small-celled phytoplankton species. We hypothesize that primary production in these communities is principally fueled by regenerated nutrients, thus promoting a low-export food web.

H1.2: Changes in phytoplankton phenology, productivity, and community composition propagate through the food web producing shifts in the zooplankton and fish communities; conditions of low export and low net community production are associated with enhanced energy flows through protozoa, filter-feeders, and smaller body-size crustaceans.

H1.3: Enhanced physiological rates of zooplankton grazers and parasites of phytoplankton during anomalously warm winters cause higher phytoplankton mortality and suppress diatom blooms, with resulting shifts toward food webs dominated by small-celled phytoplankton and lower rates of export and net community production.

Q2: *How is variability in the feeding, condition, and distribution of pelagic forage fish linked to interannual variability and multi-year trends in plankton size structure and species composition and the ratio of export to total primary production?*

H2.1: Spatial and temporal differences in species composition and abundance of the pelagic forage fish assemblage are linked to the size structure of the planktonic food web, with fish species whose diet breadth includes small zooplankton being favored under low-export conditions.

H2.2: Spatial and temporal differences in species composition and abundance of the pelagic forage fish assemblage are linked to the specific types of available zooplankton, with feeding specialists (i.e., narrow diets) being more influenced by the variability in preferred prey—and thus the high- or low-export conditions favoring those prey—rather than the aggregate of zooplankton species.

H2.3: The species-specific feeding success and nutritional condition of the pelagic forage fish present in the study region, regardless of their abundance, will vary with the abundance, size structure, and species composition of the zooplankton community and, thus, export regime observed.

Q3: *Is the NES ecosystem (and the services it provides) vulnerable to dramatic transformation in the face of rapid climate-induced environmental changes? Or does the diversity of species confer resilience, providing a buffer against dramatic changes in overall productivity via shifts in species composition?*

H3.1: Functional diversity (e.g., diet flexibility, feeding behavior) among small pelagic fish promotes stability in their biomass on multiyear time scales despite higher frequency fluctuations in planktonic food web structure.

H3.2: High levels of plankton species diversity act to maintain important trophic linkages (e.g., diatoms, mesozooplankton, fish) under current seasonal and interannual variability, but continuing environmental changes will lead to a shift to a low export production regime.

With progress towards answering these questions, our understanding of the NES ecosystem, and other temperate western boundary current systems will be vastly improved.

1.6 Background and Preliminary Results

1.6.1 Physical changes occurring in the NES

Annual mean SST in the NES region has risen about 1°C over the last century (Shearman and Lentz 2010). Furthermore, the region has experienced more rapid interannual to decadal changes in temperature recently (e.g., Mills et al. 2013; Chen et al. 2014a). The seasonal variation in SST has also increased in recent decades (Friedland and Hare 2007). Interannual variations in NES ocean temperature affect the distributions of a wide range of commercially important species (e.g., Taylor et al. 1957; Murawski 1993; Weinberg 2005; Lucey and Nye 2010; Nye et al. 2011; Overholtz et al. 2011; Walsh et al. 2015). In some cases, shifts in distributions have been linked to basin scale indices (e.g., Nye et al. 2009; Nye et al. 2011), but the linkages between these large-scale indices (e.g., North Atlantic Oscillation and Atlantic Multidecadal Oscillation) and the observed distribution shifts are unclear. There are also large interannual variations in salinity associated with both local variations in river runoff (e.g., Manning 1991) and in variations in upstream source waters (e.g., Mountain 2003) that may lead to changes in advective nutrient supply (e.g., Mountain 2012) and local stratification (Li et al. 2015).

1.6.2 Setting the stage: NOAA monitoring efforts in the NES ecosystem

The NES has been monitored over multiple decades through a variety of temporally and spatially extensive programs that evaluate the system's environmental conditions and important natural resources (Reid et al. 1999). For example, the NOAA National Marine Fisheries Service (NMFS) Northeast Fisheries Science Center (NEFSC) trawl survey (started in the 1960s) is a twice-per-year assessment of environmental parameters, zooplankton species distribution and abundance, and fish, including the commercially and ecologically important small pelagic species that prey on the planktonic assemblage. As part of the trawl surveys, the spatial and temporal distributions of many species of fishes are complemented by the extensive dataset that the Food Web Dynamics Program (FWDP) at the NEFSC has accumulated on fish feeding habits. The zooplankton sampling that occurs on the trawl surveys is also part of the EcoMon program at the NEFSC. There are typically 4 additional EcoMon-specific cruises per year devoted to sampling the planktonic environment throughout the NES (Fig. 1). These programs have yielded impressive works illustrating a number of fundamental ecological processes (Garrison 2000; Garrison and Link 2000; Overholtz et al. 2000; Link 2002; Link and Garrison 2002; Smith and Link 2010). Additionally, they have contributed to the larger goal of understanding, managing, and preserving the many components that contribute to function of the ecosystem (Levin et al. 2009; NOAA 2012) as it changes with time (Fig. 6).

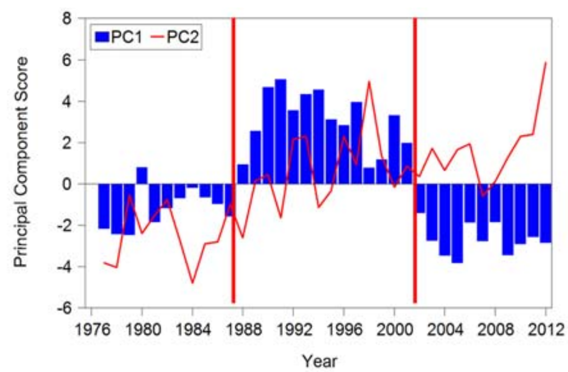

Fig. 6. Decadal-scale changes are reflected in the first two principal components of an NES Ecosystem Index that reflects contributions by climate, physical, and ecological indicators (NOAA 2015). Component 1 (PC1) points to state shifts between decades, while component 2 (PC2) reflects a longer-term trend (e.g., associated with warming).

1.6.3 Phytoplankton community shifts over multiple scales

Aspects of phytoplankton variability have been characterized in the NES ecosystem over multiple decades, principally through assessment of chlorophyll concentration (from in situ sampling and satellite observations) and through continuous plankton recorder (CPR) analyses of broad classes of microplankton (Fig. 7). This type of aggregate monitoring provides insight into patterns, but leaves many questions unanswered concerning the causes and consequences of multi-year change. Going forward, these gaps can be addressed with automated technology and ocean observing infrastructure. Multiyear observations at MVCO have already demonstrated the power of this approach to assess compositional variability at many time scales. For over a decade, PI Sosik has deployed a combination of FlowCytobot (FCB; pico/nanoplankton) and Imaging FlowCytobot (IFCB; nano/microplankton) to measure high temporal resolution taxon-specific changes in phytoplankton abundance and biomass (e.g., Fig. 4). These observations document systematic seasonal shifts in community structure, with dominance by large-celled and chain-forming diatoms in fall/winter and by picoplankton and small nanoplankton in spring/summer.

Taxon-specific interannual variability is also evident, with apparent links to temperature in certain cases. Notably, the taxon-specific, high-frequency observations at MVCO make it possible to extend beyond just describing patterns. We can begin to link the changes with physiological and ecological mechanisms that interact with environmental conditions to structure seasonal and interannual variability. For example, some taxa are favored in warm winters (Fig. 8). An important case is the dominant picophytoplankter, *Synechococcus*, for which warming conditions are also leading to earlier spring blooms (Fig. 9). By coupling these observations with trait-based matrix population models, we have shown that this bloom shift results from enhanced growth rates (linked to alleviation of physiological temperature limitation) and also that loss rates (grazing or lysis) have shifted in tandem with the autotrophs (Hunter-Cevera et al. 2016).

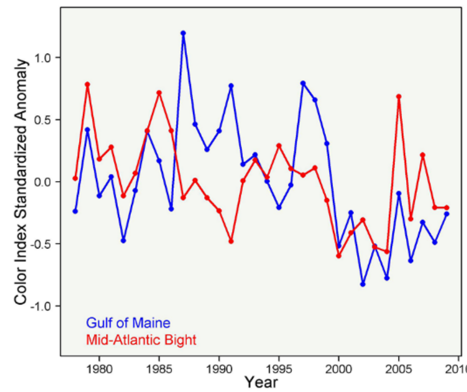

Fig. 7. Multi-decade patterns in phytoplankton color index anomalies derived from NES continuous plankton recorder transects (NOAA 2015). Due to mesh size, this index reflects an incomplete sampling of microphytoplankton.

While physiologically-mediated changes seem to be the most important driver for picophytoplankton change at MVCO over the last decade, ecological interactions may be more important for some microphytoplankton, but still with links to temperature change. For example, time series of high-resolution images have revealed that the dominant chain-forming diatom (*Guinardia delicatula*) is subject to high mortality from a nanoflagellate parasitoid (Peacock et al. 2014). The level of parasitoid infection evident in the population is a strong predictor of bloom magnitude, and warm winters are linked to enhanced infection and bloom collapse. As warming trends continue and periods of cold winter waters are reduced in duration and intensity, dramatic winter blooms of this diatom (Fig. 4) may not persist. These same conditions should lead to an increase in the prevalence of *Synechococcus* and other picophytoplankton (Fig. 8). Observations across other trophic levels and with a wider geographic range will be essential to characterize the scope and impact of these changes at the base of the NES food web. Beginning in 2013, PI Sosik and NOAA collaborators undertook the next step towards this goal by integrating continuous IFCB observations with routine EcoMon surveys. These observations are now being used to evaluate satellite-derived distributions of phytoplankton groups (Fig. 10), which already contribute to regional Ecosystem Status Reports undertaken for NES fisheries and ecosystem management (NOAA 2015). LTER-enhanced EcoMon surveys will enable these observations to continue.

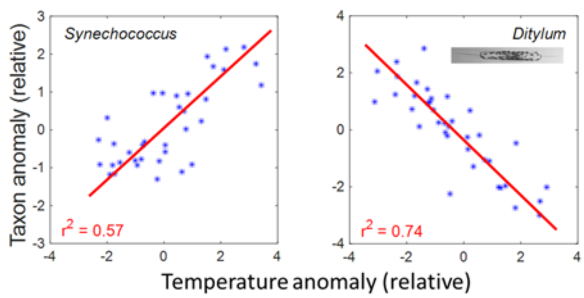

Fig. 8. Anomalies in abundance of the dominant picophytoplankter (left) and an important diatom (right) compared to temperature anomalies for January conditions at MVCO during the period 2007-2016.

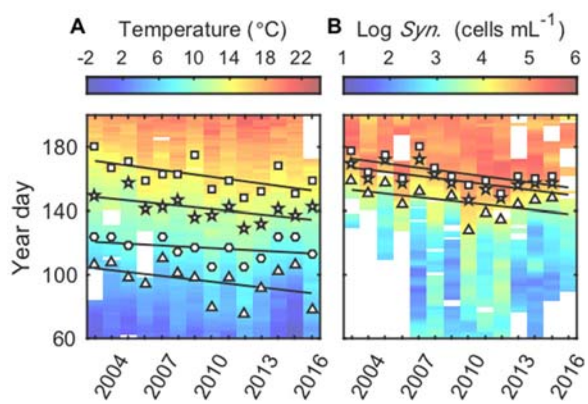

Fig. 9. Year day of threshold crossings in (A) temperature (6, 9, 12, 15 °C) and (B) *Synechococcus* concentration (10^4, $5x10^4$, 10^5 mL^{-1}) at MVCO document that spring warming and the concurrent *Synechococcus* bloom have advanced ~18 days in the period since 2003 (Hunter-Cevera et al. 2016).

1.6.4 Zooplankton variability in the NES ecosystem

Zooplankton abundances and community structure in the NES ecosystem have shown substantial interannual variability in recent decades. The greatest focus on such variability has been for the GoM and Georges Bank (Pershing et al. 2005; Greene and Pershing 2007; Kane 2007; Mountain and Kane 2010; Hare and Kane 2012). However, recent syntheses (NOAA 2015) are showing coherent trends throughout the NES. The most notable findings include a shift in zooplankton community structure that occurred in ~1990, evidenced by increased total zooplankton, as well as a distinct increase of small-bodied copepods that resulted in a shift in the overall size structure of the zooplankton community (Fig. 11). Another regime shift was evident in ~2000, when some of the earlier changes reversed, including a remarkable drop in small copepods and an increase again in the large and important copepod *Calanus finmarchicus*. While climate-related forcings (e.g., NAO) and direct and indirect effects of interactions between the Arctic and North Atlantic (Greene et al. 2013) have been implicated for many of the observations, the story is still not overly clear, and data from more recent years are suggesting that the mechanisms may be more complex than initially thought. Even less understood are how changes in zooplankton—either overall abundance or species and size composition—propagate up to higher trophic levels and ultimately fisheries.

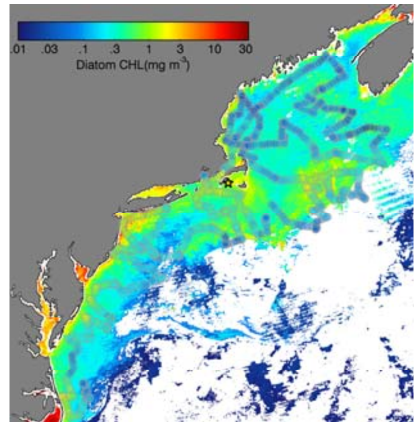

Fig. 10. Chlorophyll associated with diatoms during November 2014, as derived from MODIS with the algorithm of Pan et al. (2010; 2011), which is tuned for the NES region (image credit: K. Hyde, NOAA), with overlaid estimates of diatom biomass from IFCB as a semi-transparent color-coded cruise track (Nov 2014 EcoMon survey). For display purposes, IFCB values are scaled assuming C:Chl =10.

1.6.5 Small pelagic fish communities and their trophic role

Food web analyses of the NES fish community (e.g., Garrison and Link 2000) generally classify 6 taxa as the dominant planktivores: Atlantic herring (*Clupea harengus*), Atlantic mackerel (*Scomber scombrus*), Atlantic butterfish (*Peprilus triacanthus*), alewife (*Alosa pseudoharengus*), blueback herring (*Alosa aestivalis*), and sand lance (*Ammodytes* spp.). Differences in the life histories of these fishes are notable. Atlantic herring and Atlantic mackerel are both long-lived (>10 yr) species that undergo seasonal north-south migrations that exceed 500 km along the continental shelf. For both species, the MAB is the southern extent of their range. Atlantic butterfish is a short lived species (<3 yr) that occurs as far south as Georgia, and it undergoes both latitudinal and cross-shelf seasonal migrations in response to seasonal changes in temperature. Alewife and blueback herring are anadromous (i.e., spawn in freshwaters), but are abundant on the NES most of the year. They exhibit a degree of spatial separation, with blueback herring occupying the southern New England region in fall, while Alewife do so more in the spring. Sand lance are non-migratory, but bury in the sand for months at a time in response to changing temperatures and food availability. There are two species that are rarely distinguished. *A. americanus,* is thought to occupy only shallow waters <10 m depth, so we will focus on *A. dubius*, which will likely represent most, if not all, samples from the trawl survey. If necessary, genetic barcoding can be used to confirm species identity.

Population sizes of small pelagic fishes exhibit considerable seasonal and interannual variability in their spatial distribution patterns (Fig. 12). Multiple studies have

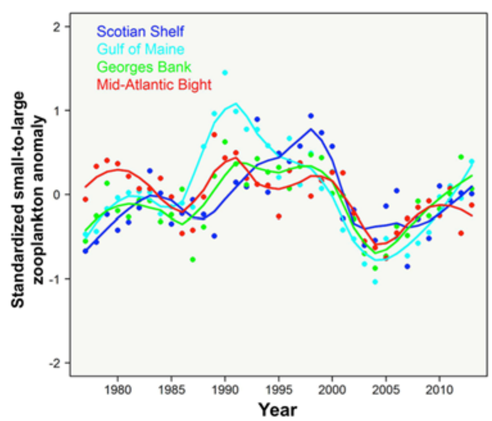

Fig. 11. Time series of a zooplankton size index for 4 regions of the NES calculated from the relative abundances of small (*Centropages typicus, C. hamatus, Temora longicornis*, and *Pseudocalanus* spp.) and large copepods (*Calanus finmarchicus*) (NOAA 2015).

documented alternating periods of dominance among these pelagic species. Fisheries reports and statistics from the early 1800s to the 1960s suggest that Atlantic mackerel and Atlantic herring were never simultaneously at high abundances (Skud 1982). When both species were fished to low levels in the 1970s, sand lance increased 10-100 fold (Sherman et al. 1981). Subsequently sand lance populations declined around 1990 before increasing again around 2006; these population trends continued to be out-of-phase with Atlantic herring (Fogarty et al. 1991; Richardson et al. 2014). Butterfish populations have higher frequency variability but are thought to have peaked in the 1980s, declined from the 1990s through 2008, and then increased again in recent years (NEFSC 2010). The trends for the three exploited species (herring, mackerel and butterfish), while clearly influenced by fishing pressure, cannot be explained by fishing alone (Fogarty et al. 1991; NEFSC 2010; Richardson et al. 2011a).

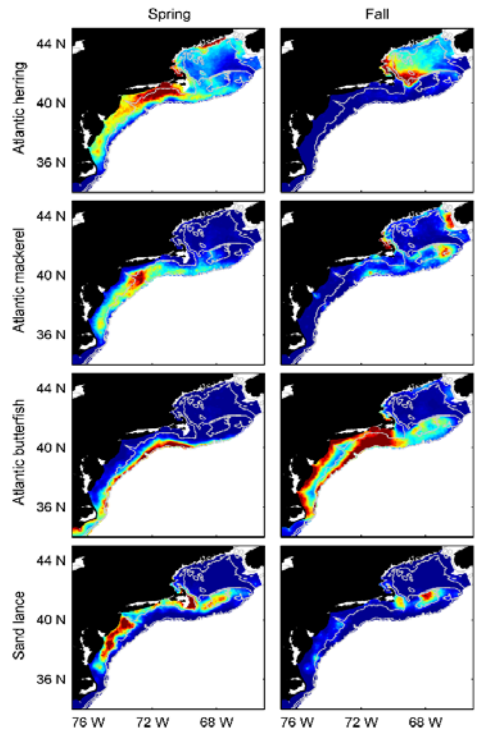

Fig. 12 Average seasonal and spatial distributions of four small pelagic fishes on NEFSC bottom trawl surveys, 1980-2008. Color maps are scaled to the maximal seasonal abundances (red = high abundance; from D. Richardson, NOAA).

Small pelagic fishes of the NES play a critical role in structuring fish communities over time and space. As intermediate consumers with relatively low diversity, these species are heavily relied on by predators, and are therefore often referred to as "forage fish". They serve as a narrow conduit for energy flow from secondary production to the more diverse upper trophic levels of groundfish, larger pelagic fishes, birds, and mammals (Overholtz et al. 2000; Read and Brownstein 2003; Overholtz and Link 2007). Large population fluctuations in small pelagic fish (Overholtz 2002; Melvin and Stephenson 2007; Richardson et al. 2011a) lead in turn to temporal variability in their total levels, altering prey availability to higher trophic levels (Overholtz et al. 2000; Overholtz and Link 2007).

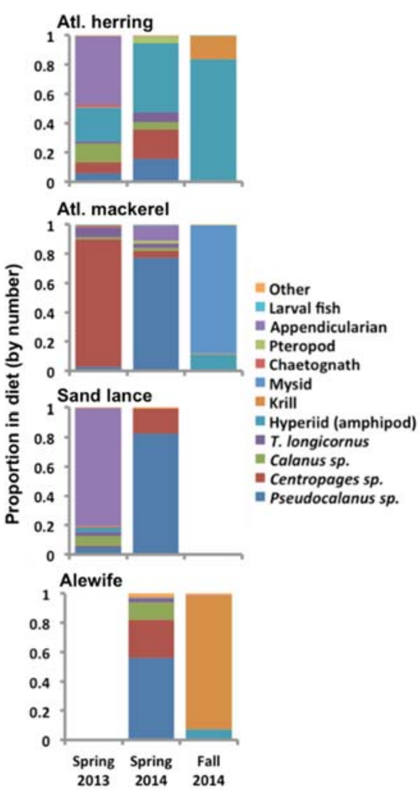

Fig. 13. Diets of 4 species of small pelagic fishes from throughout the NES region from different years and seasons.

From a top-down perspective, variation in the abundances of small pelagic fishes must lead to variation in their overall consumption of zooplankton prey. However, their top-down impacts upon total zooplankton, as well as specific zooplankton taxa, remain poorly characterized, and many questions and ambiguities remain regarding the trophodynamic role of small pelagic fishes. Gut content data from NEFSC's FWDP show indications of spatial and temporal variability in the trophic role of small pelagic fish (Smith and Link 2010), but two significant limitations of the data stand out: 1) the very broad groupings for some of the prey categories (e.g., 'copepods'); and 2) the large contribution of 'well digested prey' (i.e., unidentifiable animal remains) to the diets of most small pelagic fishes.

Ongoing work by co-PI Llopiz involves detailed microscopic examination of stomach contents of wild-caught small pelagic fishes from the NES. This effort is showing high levels of interannual and seasonal diet variability (Fig. 13), including the notable variability in feeding upon appendicularians by Atlantic herring and sand lance. Spatially, there was almost exclusive feeding on certain types of prey (e.g., appendicularians) by all fish at some sites (Fig. 14), but then no consumption at all of these prey at other sites.

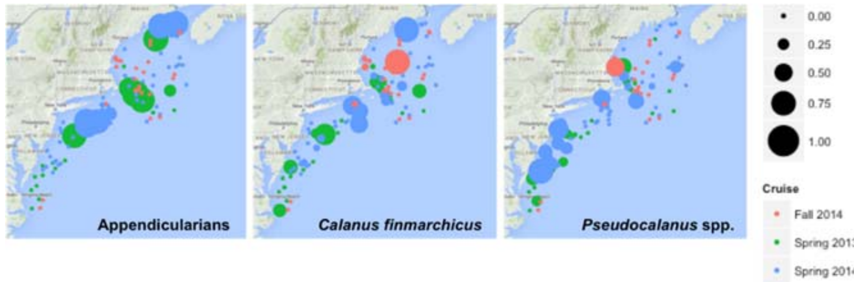

Fig. 14. Spatial and temporal variability in prey consumption by all small pelagic fishes of three zooplankton types. Circle size for each prey type represents the proportion of all prey consumed at a given station.

Stable isotope analysis (SIA) has a long history in ecological research, and it has often been used to address questions related to feeding habits, trophic levels, the food web structure of communities, and patterns of energy flow through an ecosystem (Peterson and Fry 1987; Post 2002). The utility of SIA lies in the fact that the ratios of elemental isotopes in organic tissues can vary, usually predictably, with a variety of processes. The elements most commonly analyzed in such studies are carbon and nitrogen, as their isotopic ratios (denoted by $\delta^{13}C$ and $\delta^{15}N$ with units of ‰ difference from a known standard) can provide information on diet and trophic position. Of particular interest in trophodynamic studies are the processes that determine 1) the stable isotope ratio (i.e., signature) at the base of the food web, and 2) how that signature changes from resource to consumer by the process known as trophic fractionation. The signature at the base of the food web can provide information about the primary producers and nutrient sources in the system (e.g., Fry and Sherr 1984; Vander Zanden and Rasmussen 1999; Michener and Kaufman 2007), while the systematic trophic fractionation that occurs when a resource (i.e., diet) is incorporated into the consumer provides information about that consumer's trophic level (e.g., McCutchan et al. 2003). In line with the observed species-specific and temporal variability in diets noted above, our ongoing work on the stable isotopic signatures of small pelagic fishes is revealing differences among consumers and years (Fig. 15). These results show that energy transfer from zooplankton to higher trophic levels varies spatially and temporally. Yet, many questions remain regarding the drivers and consequences of this variability.

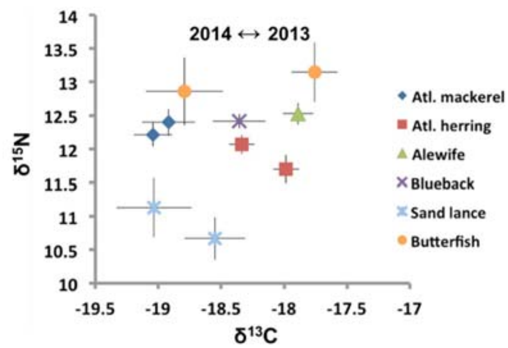

Fig. 15. Mean (±SD) stable isotope values of muscle tissue for 6 species of small pelagic fishes on the NES during the spring from two years (for 4 of 6 species). $\delta^{13}C$ values were consistently lower in 2014 than 2013.

1.6.6 Characterizing compositional variation with enhanced resolution

It is well known that plankton species cannot always be identified by their morphology. Because morphologically cryptic species are difficult or impossible to identify with methods such as light microscopy, they represent a major challenge in both documenting the taxonomic diversity of marine waters (Sims et al. 2006) and understanding the impact of species composition on marine ecosystem function and biogeochemical cycles.

Recent taxonomic efforts have described many eukaryotic phytoplankton species that are morphologically cryptic (i.e., identical) or pseudo-cryptic (i.e., small structural differences), including those in ecologically important diatom genera (e.g., Beszteri et al. 2005; Amato et al. 2007; Kooistra et al. 2008; Lundholm et al. 2012; Whittaker et al. 2012; Nanjappa et al. 2013; Kaczmarska et al. 2014). Many of these genera are abundant in the NES region. For example, the genera *Thalassiosira*, *Skeletonema*, *Chaetoceros*, *Asterionellopsis*, *Pseudo-nitzschia, Dactyliosolen and Guinardia* are all composed of cryptic species and are also abundant at MVCO. Studies have suggested that morphologically cryptic species commonly occur in phytoplankton communities (Kooistra et al. 2008; Kooistra et al. 2010;

Hamsher et al. 2013). Given this, it is likely we are missing what could be large changes in species composition, simply because we fail to “see” that the species differ.

To better identify cryptic species, high-throughput DNA sequencing has been used in several field studies, providing insights into the ecology and potential biogeochemical impacts of morphologically cryptic plankton. For example, targeted molecular analyses revealed that the numerically dominant diatom genus in Narragansett Bay, *Skeletonema*, is actually composed of seven different species whose abundances vary seasonally and that are strongly correlated with shifts in water column temperature (Fig. 16) (Canesi and Rynearson 2016). Similar shifts in species composition over space and time have been observed in the genus *Pseudo-nitzschia* (Hubbard et al. 2014; Ruggiero et al. 2015) and the diatom family Leptocylindraceae (Nanjappa et al. 2014). Insights into *Skeletonema* ecology (Fig. 16) were obtained from the Narragansett Bay time series (directly adjacent to our NES focal transect) and suggest that similar strong variations in species composition could occur in the NES on both seasonal and, potentially, decadal scales.

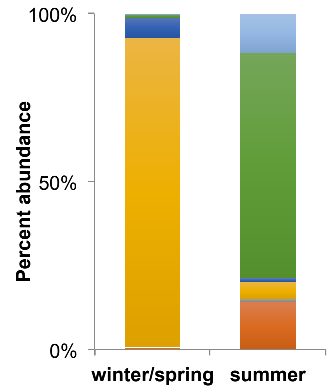

Fig. 16. High-resolution sequence data showing the diversity of *Skeletonema* species in Narragansett Bay, RI (Canesi and Rynearson 2016). Each color represents a different species. Light microscopy only identifies the genus, not the species present. Sequencing provides a window into seasonal changes in species composition that likely have ecological significance.

Observations of cryptic species distributions have been supported by physiological studies showing growth rates among cryptic species differ in response to environmental conditions such as temperature and light (Kaeriyama et al. 2011), salinity (Jackson et al. 1992), and nutrients (Maldonado et al. 2002). The physiological variation observed among cryptic species, coupled with the few studies of spatial and temporal variation described above, suggest that variation in cryptic species composition has important ecological and biogeochemical implications.

One challenge to identifying variation in cryptic species composition is that molecular characterizations of eukaryotic plankton species are not routinely conducted. This includes micro- and mesozooplankton, both of which comprise morphologically cryptic species (McManus et al. 2010; Bailey et al. in press). Thus, the analysis of these communities suffers from issues identical to those described above for eukaryotic phytoplankton. Because bacterial species have much less morphological variation, molecular analysis of bacterial populations has been routinely implemented for years. In the NES-LTER, we propose to incorporate regular molecular analysis of species composition across domains of life and across spatial and temporal scales to explore details of how climate and environmental change is influencing the relationship between compositional and aggregate ecosystem variability.

1.6.7 Productivity rates

Decades of ^{14}C-based primary productivity research on the NES, as well as productivity studies by other methods, especially when made in conjunction with phytoplankton community characteristics, have documented links between physical seasonal dynamics, phytoplankton communities, and rates of primary production (e.g., O'Reilly et al. 1987; Campbell and O'Reilly 1988; Lohrenz et al. 2002; Mouw and Yoder 2005; Fields et al. 2015). Primary production is a key aggregate ecosystem property and thus the NES-LTER will measure productivity in multiple ways on a variety of ecologically relevant temporal and spatial scales, including use of incubations, dilution experiments, and in situ gas tracers. Incubation-based ^{14}C-incorporation provides net primary production (NPP) estimates to compare with past datasets and to other ecosystem variables, as well as to constrain models. Additionally, better understanding of aggregate variability in the NES system can be achieved by estimating rates of net community production (NCP) and gross primary production (GPP) through in situ gas tracers, a method that supports greater spatial coverage than is possible with discrete incubations. Measuring all these production rates concurrently is valuable because they give fundamentally different but complementary information. Characterizing both the composition of plankton communities and the metabolic rates they support, as well as seeing how communities and rates change over time, will be necessary to gain new insight into the factors that regulate productivity in the NES ecosystem.

In particular, concurrent measurements of NCP, GPP, and NPP will allow construction of energy flow diagrams, which trace pathways of energy in the system (Fig. 17). As conditions change (season, distance from shelf, interannual variation), these energy flow diagrams are likely to change and may provide important predictors of impacts at higher trophic levels. For example, after an upwelling event in Monterey Bay, the energy flow diagram showed a shift away from autotrophic respiration toward heterotrophic respiration and a small increase in NCP (Manning, Stanley, et al. unpub). The temporal and spatial scales of the NPP measurements are much smaller than for NCP and GPP, complicating combining the three, so satellite NPP algorithms (e.g., Behrenfeld et al. 2005; Westberry et al. 2008) will be also be used (in addition to the direct information from ^{14}C-incubations and grazing rate studies) to construct energy flow budgets.

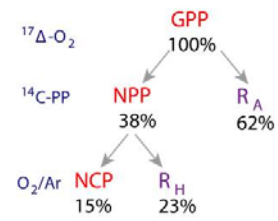

Fig. 17. Simultaneous measurements of rates of gross primary production (GPP), net primary production (NPP), and net community production (NCP) trace energy flow in an ecosystem. Shown here is the energy flow diagram before an upwelling event off California (Manning, Stanley, unpub)

Additionally, over large enough spatial and temporal scales, NCP must equal export production, since if carbon is not used locally for respiration it must be exported (Eppley and Peterson 1979). A recent study involving simultaneous measurements of NCP and export production (from ^{234}Th tracer studies) indeed showed that, although on the submescale (<10 km) NCP and export production were decoupled, on larger scales (>30 km) NCP and export production rates were in agreement (Fig. 18) (Estapa et al. 2015). Scales >30 km are likely most relevant for fisheries, and thus NCP is expected to be in agreement with export production on the spatial scales relevant to this proposed work. Furthermore, in the Sargasso Sea, when both NCP and export production are calculated by geochemical techniques they are similar (Jenkins 1988b; a; Gruber et al. 1998; Stanley et al. 2012; Emerson 2014). However, both are greater than export production estimated with sediment traps (Church et al. 2013), likely due to methodological issues with traps, including missing episodic high flux events, as well as known issues of hydrodynamic biases and swimmers (Buesseler et al. 2000; Buesseler et al. 2007). In the coastal environment, sediment traps are especially problematic (Bishop et al. 2016), so they are not an ideal choice for the proposed NES-LTER. Use of gas tracers to estimate NCP accurately and continuously (see Section 1.7.6) has the advantage of providing a wealth of data on scales ranging from several to hundreds of km, and from which we can then infer export. We anticipate incorporating ^{234}Th-based export assessment via future separately funded projects that leverage the LTER infrastructure.

A recent study by Friedland et al. (2012) showed that fisheries yields were correlated with export production rates and especially with the export ratio, as defined as export production:NPP, more strongly than they were correlated with NPP. This was based on 52 Large Marine Ecosystems—there were no significant relations within just one region. We expect that by measuring NCP (equivalent to export—see previous paragraph) *directly* within our region, as well as by studying the region over time and thus obtaining a large dynamic range of fluxes, regional links between the export ratio (NCP:GPP from gas tracer methods) and fisheries yield may emerge. Friedland et al. (2012) estimated the export ratio from a multilinear algorithm (Dunne et al. 2005), as opposed to measuring it directly, as we will do. Such algorithms are broadly adequate, but often do not match measured export production on a station-to-station basis within a given region (Stanley et al. 2010; Ayers and Lozier 2012). Thus, the lack of relationships within regions in the Friedland et al. (2012) study may be due to real variability in the system or to errors in export estimators, both of which can be overcome with more appropriate sampling and methods.

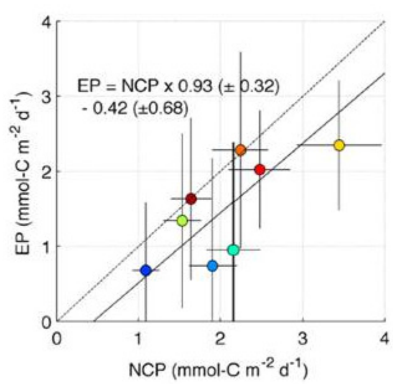

Fig. 18. On large spatial scales (>10 km), NCP and export production (EP) are strongly correlated (data from Sargasso Sea). EP rates were determined from ^{234}Th, averaged on 30 km transects, and NCP rates were from O_2/Ar, averaged on the same transects (Estapa et al. 2015).

1.6.8 Ecosystem modeling

A diverse set of ecosystem models have been, and continue to be, developed for application in the NES region; these range from process-oriented models focused on nutrient transport dynamics (e.g., Hu et al. 2008; Ji et al. 2008a; Zhang et al. 2013), to shelf-wide biogeochemical (e.g., Fennel et al. 2006; Fennel and Wilkin 2009) and lower-trophic level food web (Ji et al. 2008b; Tian et al. 2014) models, to end-to-end models that include higher trophic levels (e.g., Link et al. 2010). These models have demonstrated various connections of physical forcing with biological responses and interactions, and they have clarified our understanding of local and regional drivers of observed patterns and variability. Modeling tools developed through previous efforts, and the knowledge gained from them, provide a strong foundation for the proposed NES-LTER.

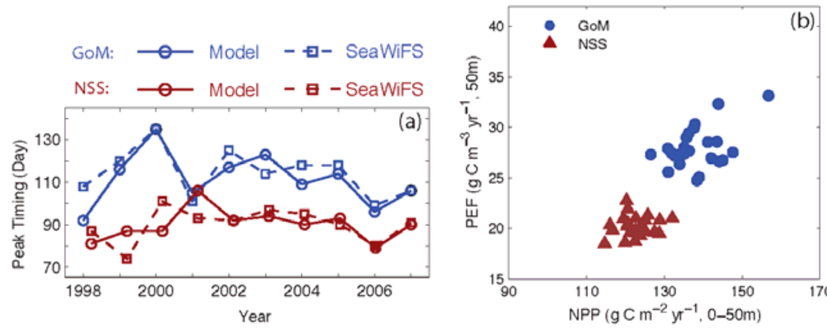

Fig. 19. (a) Comparison of modeled and SeaWiFS-derived spring bloom peak timing in the Gulf of Maine (GoM) and the Nova Scotian Shelf (NSS) region (a) and associated relationships between annual net primary production (NPP) and annual particle export flux (PEF) (b). Adapted from Song et al. (2011).

To quantify compositional and aggregate variability, and to identify drivers for changing production and export regimes on the NES, a model needs to have sufficient physical and biological resolution to resolve relevant dynamics and patterns of disturbance. The high-resolution Finite Volume Community Ocean Model (FVCOM) developed for this region has been shown to resolve both regional-scale circulation and local fronts and stratification (see Section 1.7.9). For the biological dynamics, the model must be able to resolve key aspects of compositional variability (e.g., small/large phytoplankton and zooplankton, inorganic and organic material in various forms), and to make useful inferences about aggregate properties (such as standing stocks, recycled vs. export production, NCP) and how they are linked to the environment and changes in forcing. An intermediate complexity model originally developed by Stock and Dunne (2010) has proven capability for these objectives. The model already includes simple size structure in plankton functional groups and has been tested in the GoM in a 1-D setting (Song et al. 2010; Song et al. 2011). Notably, simulations show correspondence between observations and model-simulated phytoplankton bloom timing, and the model predicts interannual variability and regional differences in response to different stratification regimes (Fig. 19a). Model results suggest that bloom timing can affect annual NPP and particle export flux (PEF): regions with an earlier spring bloom have lower NPP due to enhanced stratification and weaker nutrient supply from deep water, which in turn leads to weaker export (Fig. 19b). Whether these or similar patterns can be generalized throughout the NES and how they are linked to higher trophic levels are important outstanding questions (Section 1.5), which demand a combination of modeling and multi-faceted observations.

1.7 Approach and Method Details

Our approach integrates long-term observations, process and experimental studies, and models. The long-term observations (a) span the regional scale via enhanced sampling on quarterly NOAA survey cruises; (b) capture cross-shelf gradients via quarterly focal transect cruises from MVCO to the OOI Pioneer Array; and (c) examine the local scale via high-temporal-resolution measurements at MVCO and the OOI array (Fig. 1). We will focus on characterizing the physical environment; inorganic nutrients; abundance, biomass, and composition of pelagic organisms by trophic level; primary production and NCP (Table 2). Process and experimental studies will target population dynamics of plankton by major taxa, rate processes via incubations, and trophic assessments via species-specific diet and stable isotope analyses. Additional local-to-regional context will be provided by remote sensing (e.g., SST, chlorophyll, NPP). A biological-physical coupled food web model will be used for synthesis and hypothesis testing, and more targeted population models will be used to investigate physiological, behavioral or other aspects of organism-specific processes for a range of taxa (plankton to fish). As summarized in Section 1.8, these approaches taken together cover the five LTER core areas.

1.7.1 LTER enhancement of regional NOAA surveys

By partnering with the NMFS NEFSC, we will leverage regional surveys focused on ecosystem monitoring and fisheries stock assessment; these surveys have been ongoing for decades and provide critical information for historical context and current status (Table 1). Quarterly EcoMon cruises are dedicated to plankton and hydrographic data collection throughout the NES (Fig. 1, Table 2). In addition to NOAA-supported sampling of nutrients, zooplankton, and ichthyoplankton, we propose LTER enhancements enabling automated underway analysis for phytoplankton and NCP, and selected station sampling for GPP and plankton genetic diversity (described below). We have an established partnership with NOAA scientists, have already begun routine automated plankton imaging on EcoMon cruises (since 2013, e.g., Fig. 10), and our experience suggests these EcoMon enhancements can be achieved with minimal routine investment (i.e., a single LTER-project cruise participant). We will also take advantage of fish stock assessments and fish specimen collection from twice-yearly NOAA trawl surveys (including pelagic fish assessments) on the NES. These surveys will provide most of the specimens of the six forage fish species that will be used for diet, condition, and stable isotope analysis.

1.7.2 Process cruises on the LTER transect

Cross-shelf gradients in physical properties, nutrients, production rates, and plankton will be characterized quarterly on OOI Pioneer Array service cruises and dedicated LTER cruises. Additional LTER cruises (coastal vessel, day trips) will allow monthly sampling at MVCO. LTER cruises will include depth profiles, incubation experiments (on select cruises chosen to span seasons and internanual variations), and other process sampling.

1.7.3 Ocean observatories: MVCO and OOI Pioneer Array

Two existing ocean observatories enable high-resolution measurements at the nearshore (MVCO) and offshore (OOI Pioneer Array) ends of the LTER focal transect (Fig. 1). These continuous observations provide insight into scales of variability and processes influencing the inner shelf and shelf break.

MVCO (41° 19.5' N, 70° 34.0' W) has been operated by the Woods Hole Oceanographic Institution (WHOI) since 2001 and directed by PI Sosik since 2006. MVCO is located south of the island of Martha’s Vineyard, MA. This cabled facility provides power and communications at a meteorological mast, an undersea node at a depth of 12 m, and 3 km offshore at a tower structure, which spans the water column (15 m water depth) and extends approximately 20 m into the atmosphere (Fredericks et al. 2006). Many temporal scales of environmental variability are evident from routine high-frequency meteorological and hydrographic core measurements, which are publically accessible for both archived and real-time data (WHOI 2016). PI Sosik and collaborators have maintained a unique time series at MVCO since 2003 with submersible flow cytometers (Olson et al. 2003; Olson and Sosik 2007) that provide high temporal and taxonomic resolution information about phytoplankton communities. As part of the proposed NES-LTER, current observations at MVCO focused on physical, chemical, and phytoplankton properties will be continued, and enhancements will include continuous temperature, salinity, and density profiles, continuous zooplankton abundance and species composition, and discrete measurements of gas-tracer based production. The accessibility, high data band-width, and power availability at MVCO enable this cutting-edge combination of in situ observations and discrete sampling, which is highly expandable as new technologies emerge. For example, we anticipate future integration of such possibilities as fully autonomous gas-tracer-based primary production assessments and field-deployable DNA sequencers.

The OOI Pioneer Array includes a combination of moorings, autonomous vehicles (AUV), and gliders collecting physical, bio-optical, and chemical data. The Pioneer Array is centered at the shelf break (~40° 8' N, 70° 50' W) south of MVCO to study processes and exchange across the shelf-break front separating cool, fresh shelf water from warmer, saltier slope water. Initial deployments began in late fall 2012 and the array was fully commissioned in 2015. The frontal-scale moored array consists of 4 sites between the 90-m and the 450-m isobaths (~40 km) and 3 sites 7.5 km to the east. A suite of 6 gliders sample a 130 km-by-185 km region of the outer shelf and continental slope around the moored array (39-40.67°N 69.9-71.5°W). The OOI observations are archived and publicly accessible (OOI 2016). The Pioneer Array provides an unprecedented suite of detailed observations in the vicinity of the dynamic and complex shelf break front. This is an asset for the proposed LTER because quantifying cross-shelf and vertical exchange and understanding the processes contributing to that exchange is a challenge for the NES region. While cost limits preclude us from including addition of LTER-specific sensors to the Pioneer Array, we anticipate pursuing separately funded efforts, for instance, to add plankton imaging systems.

1.7.4 Physical oceanographic, meteorological, optical, and chemical observations

Physical and chemical observations will be made throughout the region on a number of platforms: MVCO, the OOI Pioneer Array, weather buoys, and cruises. In particular, meteorological and surface ocean properties (e.g., temperature, surface waves) are available from NOAA weather buoys (NDBC), wave buoys (CDIP), and other observing systems (e.g., NERACOOS and LISICOS buoys) distributed throughout the region (Fig. 1, Table 1). Core observations supported by the MVCO facility include air and water temperature, salinity, current speed and direction, wave height and direction, wave period, tidal height, wind speed and direction, incident shortwave and infrared radiation, precipitation, relative humidity, and atmospheric pressure. Ongoing measurements also include chlorophyll fluorescence, dissolved organic matter (CDOM) fluorescence, and optical backscattering. Furthermore, since 2006 the MVCO offshore tower has been an AERONET-OC site (Zibordi et al. 2009) for measurement of atmospheric optical properties and above-water measurement of multi-spectral water-leaving radiance (for validation and development of ocean color remote sensing products in coastal conditions). We will enhance MVCO observations by deploying a mooring supporting four sensors (SeaBird MicroCat) to continuously measure the temperature, salinity, and density profiles near the offshore tower.

The Pioneer Array includes 3 surface moorings, 5 moored profilers, and 2 surface-piercing profilers. The surface moorings support a full suite of meteorological sensors for making both bulk air-sea flux estimates and direct covariance flux estimates, measurements of surface wave spectra, and surface pCO_2 and pH. Subsurface measurements include spectral irradiance, fluorescence, absorption, attenuation, nitrate, pH, O_2, temperature, and salinity. The profilers measure temperature, salinity, pressure, currents, O_2, chlorophyll fluorescence, and visible radiation (PAR). Additionally, there are upward-looking current profilers at each site. The Pioneer Array gliders carry sensors for temperature, salinity, pressure, currents, O_2, fluorescence, and PAR.

Discrete samples will be collected and analyzed for pigments, particulate organic carbon and nitrogen (POC, PON), and inorganic nutrients. Particulates from water samples (~100 mL) will be collected onto GFF filters, stored frozen, and then extracted for later fluorometric analysis of chlorophyll concentration. Additional volumes (~0.5-1 L) will be filtered onto combusted GFF filters, stored in combusted glass vials, and dried at 60˚C for later analysis of POC and PON concentration at WHOI's Nutrient Analytical Facility with standard CHN analyzer techniques. Water samples will be syringe-filtered (0.2 µm), stored frozen, and later processed at WHOI's Nutrient Analytical Facility with standard AutoAnalyzer techniques to determine concentrations of NO_3+NO_2, NH_4, PO_4, and SiO_4.

1.7.5 Functional groups, community composition and carbon-based biomass estimates

Plankton <200µm—The abundance and species composition of phytoplankton and heterotrophic protists up to 200 µm in size will be analyzed with four complementary approaches: conventional flow cytometry, imaging flow cytometry, microscopy, and DNA sequencing. Heterotrophic bacteria and autotrophic pico- and nanoplankton will be enumerated by flow cytometry (BD Accuri C6) conducted on discrete samples (preserved and stored in liquid nitrogen prior to analysis, and addition of SYBR Green dye for heterotroph detection) (Marie et al. 2005; Marie et al. 2014). In addition, continuous operation of FlowCytobot (Olson et al. 2003) at MVCO will provide high-resolution time series of pico- and nanophytoplankton (e.g., Fig. 4). Large nanoplankton and microplankton (including herbivorous protozoa and mixotrophs) will be quantified with automated operation of Imaging FlowCytobot (McLane Research, Inc.) (Olson and Sosik 2007), with submersible deployments at MVCO and continuous underway operation on LTER transect and EcoMon cruises (e.g., Fig. 4, Fig. 10). IFCB produces large numbers of images (typically 10^5 h^{-1}) that will be automatically analyzed and assigned to taxonomic groups following approaches we developed for the multi-year IFCB time series at MVCO (Sosik and Olson 2007; Peacock et al. 2014). These large data sets are challenging to manage and make accessible, but we will build from a foundation of workflows and web services already in place in the Sosik lab (Sosik and Futrelle 2012); for example, 100s of millions of images and image products used to produce the results in Fig. 4, Fig. 8, and Fig. 10 are openly accessible for browse and download (Sosik et al. 2016). For taxonomic identification, we manually inspect and identify selected images to produce training sets to develop automated classifiers (genus or species level) following the approach in Sosik and Olson (2007), except with a Random Forest classifier algorithm (Breiman 2001). We have shown that IFCB can sample many phytoplankton taxa with performance exceeding conventional manual microscopy (Olson and Sosik 2007; Campbell et al. 2010; Brosnahan et al. 2016). For selected samples, microscopy will be used to assess the nano- and micro-plankton abundance (Lund et al. 1958), particularly for taxa that are not well-resolved in IFCB images such as small dinoflagellates and species within certain diatom genera (e.g., *Chaetoceros*, *Pseudonitzchia*).

Size spectra of pico-to-microplankton will be determined by combining information from different measurement approaches. From flow cytometry analyses, individual cell light scattering will be converted into cell volume estimates on the basis of calibration with independently sized cell cultures following approaches we have previously developed (DuRand et al. 2002; Olson et al. 2003; Laney and Sosik 2014). For large nanoplankton and microplankton, we will use automated image analysis to estimate dimensions and individual cell biovolumes with approaches that are robust even for highly irregular shapes (Sosik and Olson 2007; Moberg and Sosik 2012). For microscopy, size measurements of specimens (30-100 cells per genus) will be used to compute cell volumes. In all cases, carbon-based biomass will be estimated from cell volume (Menden-Deuer and Lessard 2000) and budgets will be computed at various taxonomic levels (e.g., single species, all diatoms, etc.) and across size ranges (e.g., pico-, nano-, micro-) by summing over the relevant cells in a known sample volume. These estimates will be used in conjunction with modeling and trophic transfer and biological production rate assessments.

DNA sequencing will be conducted to identify temporal and spatial variation among bacteria and morphologically cryptic eukaryotes on the basis of DNA extracted from size fractionated filters (0.2-10 μm, 10-200 μm). For eukaryotic plankton, amplicons will be generated from two regions of the rDNA: the 18S V4 (Stoeck et al. 2010) and the 28S D1-D3 hypervariable regions. The V4 region has broad taxonomic coverage, while the 28S rDNA subunit has high resolving power to distinguish among morphologically cryptic species (Sarno et al. 2005; Whittaker et al. 2012) that will likely be important in field samples, including *Skeletonema*, *Thalassiosira* and *Chaetoceros* (Marshall 1971; Gould and Fryxell 1988; Rynearson et al. 2013). For bacterioplankton, amplicons will be generated from the 16S V6 hypervariable region (Eren et al. 2013). Amplicons will be multiplexed and sequenced on an Illumina Mi-Seq platform. Data will be processed with existing pipelines in the Rynearson lab (Canesi and Rynearson 2016) that include Qiime, USEARCH, and minimum entropy decomposition (Eren et al. 2013; Eren et al. 2015), and Operational Taxonomic Units (OTUs) identified from the SILVA-ARB database (Pruesse et al. 2007) and the Global Assignment of Sequence Taxonomy (Amaral-Zettler et al. 2009) using a shared computer cluster.

Comparisons of community composition among samples will be conducted as follows. For sequence data, similarity among samples will be determined with Jaccard similarity indices and cluster analyses (e.g., unweighted pair group method with arithmetic mean analysis). BIO-ENV will be used to identify environmental correlates using Primer V6 (Clarke et al. 2014). These analyses will be based on presence-absence of taxa rather than relative abundance due to the multi-copy nature of the rDNA cistron in eukaryotes. Similar statistics will be conducted for bacterioplankton sequence data and microscopy samples, except that these will take into account relative differences in taxon abundance (e.g., Chao1 and Shannon diversity indices). Comparisons between samples will also be made from phylogenetic information (e.g., clustering of cryptic species, family and genus-level comparisons) and the analytical approaches outlined in Martin (2002). High-resolution taxonomic information will be used to inform interpretation of the flow cytometry, IFCB analyses, and rate measurements, allowing us to examine how species composition at various taxonomic levels ranging from the broad (e.g., all diatoms, family-level responses) to the specific (e.g., genus- and species-level responses) influences population dynamics.

Metazoan diversity and biomass—Ongoing analyses of zooplankton species composition from net tow samples collected on regional cruises will be continued as part of routine EcoMon surveys. Additionally, on the NEFSC trawl surveys, plankton sampling occurs at ~120 of the ~350 trawl stations. On these surveys, plankton sampling is by 60-cm bongo net (330-μm mesh) towed to within 5 m of the bottom (or to a maximum depth of 200 m) for a minimum of 5 min. After removal of non-plankton and contaminant material, the displacement volume is determined and recorded. An aliquot of formalin-preserved sample (~500 organisms) is taken for sorting, identification, and enumeration according to taxonomic categories, including species for major groups of animals (according to approaches used for decades for NEFSC zooplankton samples). We will collect additional net tow samples with EcoMon techniques on LTER transect cruises and at MVCO, and these will be analyzed by microscopy and by DNA sequencing (see below). Automated imaging of mesoplankton will also be conducted with submersible CPICS instruments (CoastalOceanVision, Inc.) deployed for times series observations at MVCO and on CTD/rosette casts on transect cruises. Automated analysis of CPICS images for taxonomic classification and size measurement of zooplankton (plus aggregates and phytoplankton chains >200 μm) will be done with custom algorithms developed by the manufacturer.

To identify diversity among morphologically cryptic metazoans (>200 μm), splits from net tow samples collected from each station will be fixed (95% EtOH) and homogenized (via blender) prior to DNA extraction. Amplicons generated for the eukaryotic 18S rRNA gene V4-targeted hypervariable region (Stoeck et al. 2010) and a region of the cytochrome c oxidase subunit I gene (COI) (Geller et al. 2013) will be sequenced on an Illumina platform. Samples will be identified to nearest taxon with the pipeline described above for 18S diversity and as in Leray et al. (2013) for COI diversity. Fish eggs will be sorted from survey and time series samples and identified with DNA sequencing. Eggs are notoriously difficult to identify to species (Berrien and Sibunka 2006); for instance, collaborator D. Richardson (see letter in Supplementary Documents) has used sequencing to identify 12 species that are not in the NMFS trawl survey records (1961-present) and 7 species that are not in the EcoMon records (1971-present). Thus, we expect this approach will provide novel insights into fish biodiversity.

Fish diversity and abundance data will be collected during NOAA's NEFSC annual spring and fall trawl surveys. The surveys comprise 4 to 6 legs and follow a well-established sampling protocol throughout the four regions of the NES ecosystem (Reid et al., 1999; Stauffer, 2004). Surveys employ a 4-seam net towed for 20 min at 3 knots. All fish collected are identified and measured by NEFSC research staff; at each station, two fish are used for NEFSC measurements (visual inspection of gut contents; otolith extraction). All other fish caught are typically discarded and will be available to this project—specifically the six species of small planktivorous fishes examined for diets and stable isotopes (see below). Additionally, the guts of groundfish collected on the trawl surveys will be used to provide an indication of diet components of some important benthic consumers. We will seek to incorporate more detailed benthic components through separately funded projects that leverage the LTER infrastructure.

1.7.6 Rate processes and trophic analyses

Net community production—NCP will be determined *in situ* from the geochemical tracer O_2/Ar (Craig and Hayward 1987; Spitzer and Jenkins 1989; Emerson et al. 1991). The O_2/Ar approach takes advantage of the similar solubility (Garcia and Gordon 1992; Hamme and Emerson 2004) and molecular diffusivity (Jähne et al. 1987) of O_2 and Ar to quantify net biological production of oxygen, while correcting for physical processes. This method has been used since the late 1980s to constrain rates of NCP (Bender et al. 1999; Hendricks et al. 2004; Juranek and Quay 2005; Cassar et al. 2007; Reuer et al. 2007; Quay et al. 2010; Juranek et al. 2012). A recent exciting advance is the development of an at-sea mass spectrometer that allows continuous measurement of O_2/Ar from the underway system of a ship (Cassar et al. 2009; Stanley et al. 2010; Hamme et al. 2012). In the NES-LTER, NCP rates will be calculated from measurements of O_2/Ar determined continuously (spatial resolution of ~ 2 km, depending on ship speed) from an equilibrator inlet mass spectrometer (EIMS) (Cassar et al. 2009; Hamme et al. 2012; Estapa et al. 2015) on the LTER transect and EcoMon cruises, and determined on select discrete samples on all cruises. Solving mass balance equations, including estimates of gas exchange, allows O_2/Ar ratios to be converted to rates of NCP (Hendricks et al. 2004; Juranek and Quay 2005). Corrections for vertical and horizontal mixing, entrainment, and time rate of change, will be made as appropriate (Jonsson et al. 2013; Haskell et al. 2016). Frequent profiles taken with discrete samples (see next section for details), combined with associated physical oceanographic data and data-assimilative model fields, will allow these corrections to be made even in this physically dynamic region. Measurements of NCP from gas tracers include the contribution of dissolved organic carbon. We will estimate the particulate export flux from NCP by assuming a constant dissolved fraction, since recent work has shown that dissolved production as 15–20% of new production (and thus of NCP) applies throughout the oceans, even in a range of flux conditions (Romera-Castillo et al. 2016). Gliders operating at the OOI Pioneer Array collect O_2 data that can also be used to calculate rates of NCP (Alkire et al. 2014; Nicholson et al. 2015). While we are not initially proposing this work (due to budget and time constraints), we will encourage collaborations with affiliated researchers interested in producing these independent estimates of NCP that have high spatial and temporal resolution over the outer shelf.

Gross primary production—Triple isotopes of dissolved O_2, measured on cruises both discretely from the underway system and from CTD profiles, will be used to quantify GPP (Luz et al. 1999; Luz and Barkan 2000b). The triple O_2 isotope approach rests on the observation that photochemical reactions in the stratosphere fractionate O_2 isotopes in a mass *independent* way (Thiemens et al. 1995; Lammerzahl et al. 2002), whereas photosynthesis fractionates O_2 in a mass dependent way. The triple isotopic signature can be quantified by $^{17}\Delta$ (which is defined as $^{17}\Delta = [\ln(\delta^{17}O/1000 + 1) - 0.518 \ln(\delta^{18}O/1000 + 1)] \times 10^6$). Respiration is a process that removes O_2 in a mass-dependent way and thus does not affect $^{17}\Delta$ (Luz et al. 1999; Luz and Barkan 2000a; 2009). Thus the triple isotope composition of the dissolved O_2 in water serves as a "made-in tag"—it allows one to quantify what percentage of the O_2 was made by photosynthesis (shown by a higher $^{17}\Delta$) and what percentage was mixed in from air-sea gas exchange (shown by a lower $^{17}\Delta$). In short, this triple O_2 isotope technique quantifies photosynthesis only and allows one to calculate GPP rates without necessitating any assumptions about light or dark respiration.

GPP rates will be calculated from triple O_2 isotopic ratios ($^{17}\Delta$, $\delta^{17}O$ and $\delta^{18}O$) measured on discrete samples collected at MVCO and on the focal transect and EcoMon cruises. A mix of surface and profile samples will be collected, with fewer samples collected on EcoMon cruises in the last two years as data from previous years will inform sampling plans to make best use of limited resources. The samples will be collected in custom-made, pre-poisoned evacuated flasks (Emerson et al., 1991) and measured on the triple O_2 isotope processing line and isotope ratio mass spectrometer at WHOI (Stanley and Howard 2013; Stanley et al. 2015). Rigorous quality control is performed through daily analysis of air standards and equilibrated water samples. O_2/Ar ratios will be measured on the same samples, allowing ratios of NCP/GPP to be calculated and to provide confirmation for the EIMS values. Rates of GPP will be calculated from $\delta^{17}O$ and $\delta^{18}O$ (Prokopenko et al. 2011) with corrections made for entrainment and vertical and horizontal mixing (Nicholson et al. 2014; Howard et al. 2016). As is the case for O_2/Ar, spatial surveys, depth profiles, physical oceanographic data, and model results will give the information necessary for these corrections.

Rates of net primary production and bacteria production—On select transects and MVCO process cruises, carbon fixation rates will be measured by determining uptake rates of radiolabelled carbon (^{14}C) by phytoplankton in parallel with the incubations measuring phytoplankton growth and herbivorous microzooplankton grazing rates (described below). Known quantities of ^{14}C-labeled sodium bicarbonate will be added to seawater (200 µm pre-filtered to exclude large grazers) before incubation under simulated in situ light and temperature conditions in shipboard incubators. Incubations will be terminated after 12 hours (Marra 2009) by acidifying samples, which leads to neutralization and outgassing of residual labeled bicarbonate. Scintillation cocktail (Ecoscint XR, National Diagnostics) will be added and decay rate determined by scintillation counter (Packard 1900 TR). See Menden-Deuer (2012) for details.

On a subset of process cruises, bulk heterotrophic bacterial production from ^3H-leucine incorporation will be used to characterize average community rates across broad taxa (Kirchman 1992), with the primary objective to constrain parameters for bacterial processes in the ecosystem model (see Section 1.6.8). We are aware of developing single cell approaches incorporating fluorescence in situ hybridization (FISH) to provide further detail on group specific growth and activity levels (Kirchman 2016) and, given our analysis capacity, will incorporate these when possible to assess their contribution to our understanding of important features of microbial diversity, abundance, and turnover rates. More detailed studies of the bacteria will be encouraged via affiliated researchers.

1.7.7 Plankton growth and grazing rates

Measurements of plankton growth and mortality rates will be made with the dilution method (Landry and Hasset 1982; Calbet and Landry 2004). The method consists of whole seawater (WSW) collection, dilution of the WSW along a concentration gradient, and incubation at simulated in situ light and temperature conditions in shipboard incubators. A nutrient control will be included. Initial and final Chl a concentrations will be measured with the methods of Graff and Rynearson (2011), along with analysis of species abundance and composition. Concentration change as a function of dilution level yields phytoplankton growth and predator grazing rates. See Morison and Menden-Deuer (2015) for details.

1.7.8 Forage fish and zooplankton trophic dynamics

Because of their key trophic position, we will focus study on six species of planktivorous small pelagic fishes (‘forage fish’): Atlantic herring, Atlantic mackerel, Atlantic butterfish, alewife, blueback herring, and sand lance. Specimens will be collected during spring and fall NEFSC trawl surveys each year. Specimens analyzed for diets and stable isotopes will be restricted to the southern New England subregion (NY/NJ Bight to Georges Bank) in the vicinity of the LTER focal transect, while forage fish abundances for all of the NES will be included in our analyses.

At each station, fish specimens for diet and stable isotope analysis will be frozen in a -80°C freezer immediately upon recovery of the trawl sample to minimize continued digestion and degradation of consumed prey. Specimens analyzed will be selected randomly from all the species as a whole, and, thus, numbers per species per station will be determined by the catch distribution. A total of 400 fish per year (200 per survey) will be analyzed for prey composition and bulk stable isotopes ($\delta^{13}C$ and $\delta^{15}N$). In the laboratory, tissue samples of dorsal musculature will be removed from fish for stable isotope analysis, and the entire alimentary canal will be removed, weighed, and then opened to remove and preserve (in 95% EtOH) the contents. Fish will be measured and weighed (eviscerated weight) for calculating Fulton’s K condition index, and livers will be weighed for calculating a hepatosomatic (condition) index. Gut contents will be examined with high-resolution stereomicroscopy and prey will be identified to the lowest taxonomic level possible, enumerated, and measured.

To better link fish diets with their stable isotope values, and allow for interpreting these observations as they relate to the zooplankton community, stable isotope analyses will also be performed on zooplankton. Analyses will be for different size fractions of the entire zooplankton community, as well as for individual dominant taxa. Size fractions will be 20–100 µm, 100–200 µm, 200–500 µm, and 500–1000 µm. Dominant taxa to be analyzed will be the copepods *Calanus finmarchicus*, *Centropages* spp., and *Pseudocalanus* spp., as well as appendicularians and chaetognaths. Size fraction samples will be analyzed from trawl survey stations where zooplankton and examined forage fish are concurrently collected, as well as at all stations sampled during the transect cruises. Individual-taxa analyses will occur for a subset of the transect cruise stations, due to the time consuming nature of sorting zooplankton by taxa immediately upon collection.

For stable isotope analyses, samples of zooplankton and fish dorsal musculature will be dried at 60°C to a constant weight and homogenized. Samples (~1 mg) will be analyzed by the UC Davis Stable Isotope Facility, which follows well-established protocols for analyzing bulk tissue for $\delta^{13}C$ and $\delta^{15}N$ (Fry 2006; Elsdon et al. 2010; Douglass et al. 2011). C:N ratios will allow for the calculation of lipid-corrected values of $\delta^{13}C$ (Post et al. 2007; Logan et al. 2008).

Diet data analyses will range from the well-accepted descriptors of diet and feeding selectivity (e.g., Llopiz and Cowen 2008; Llopiz 2013) to multivariate approaches that incorporate oceanographic conditions, prey availability data (when plankton tows occurred at the same station), and spatial and temporal distributions (Llopiz and Cowen 2009). For the stable isotope work, effort will be directed toward examining whether and why base-of-the-food-web signatures might vary with zooplankton size fraction and taxon, and forage fish species and diet.

1.7.9 Coupled biological-physical models

Physical model—The Northeast Coastal Ocean Forecast System (NECOFS), which serves as one component of the NOAA's IOOS-funded NERACOOS, will be used as a physical model for this project. The NECOFS is an integrated atmosphere/surface wave/ocean forecast model system designed for the northeast US coastal region covering a computational domain from the Delaware shelf to the eastern end of the Nova Scotia shelf (Fig. 1). The system includes 1) a community mesoscale meteorological Weather Research and Forecasting (WRF) model; 2) a regional FVCOM with the computational domain covering the NES; 3) the unstructured-grid surface wave model (FVCOM-SWAVE) modified from SWAN (Qi et al. 2009) with the same domain; and 4) the Massachusetts Coastal FVCOM and Massachusetts Bay FVCOM, with inclusion of estuaries, inlets, harbors and intertidal wetland. The regional FVCOM grid features unstructured triangular meshes with horizontal resolution of ~ 0.3–25 km and a total of 45 layers in the vertical. The regional FVCOM is nested with a global ocean model (Global-FVCOM), which provides the upstream and open ocean boundary conditions. The NECOFS was placed into 24/7 forecast operations in late 2007, and we have continued to improve the core components of NECOFS to the present. With the regional FVCOM model nested within the Global-FVCOM system, we have conducted a 38-year (1978-2015) hindcast simulation with data assimilation of SST, SSH, and T/S profiles for a domain covering the entire NES. This simulation includes 1) the surface heat flux, wind forcing, precipitation minus evaporation, and river discharges; 2) the inflow of cool, lower salinity water from the upstream Scotian Shelf; and 3) interaction with the Gulf Stream. The 38-year hindcast fields have successfully captured the spatial and temporal variability of the physical field in the region, with support from publications, including Cowles et al. (2008) for vertical mixing and subtidal currents; Chen et al. (2011) for tidal elevations and currents; Li et al. (2015) for water stratification; and Sun et al. (2016) for CODAR-derived surface currents. The Global-FVCOM, which provides boundary forcing for NECOFS, has been also validated via climatological observations (Chen et al. 2016; Zhang et al. 2016a; Zhang et al. 2016b; Zhang et al. 2016c). For modeled physical properties, stratification is probably the most difficult to simulate, and yet has a profound impact on biological processes. A comprehensive model-data comparison has shown that the modeled stratification has largely captured the observed spatio-temporal variation, with a correlation coefficient (r) >0.9 and a normalized RMS error <0.4.

Within the scope of this project we will 1) refine the NECOFS grid to better resolve observed multi-scale physical processes over the shelf break; 2) improve the simulation of water stratification, mixing, and mid-shelf currents; 3) validate the physical model with data from the OOI Pioneer Array and other proposed NES-LTER observations; 4) develop an advanced ensemble Kalman filter adaptive data assimilation technology to incorporate these data sets, with the aim of building the best knowledge-based physical field to drive the biological model; 5) build high-resolution hindcast fields for the proposed NES-LTER program years and combine them with the existing 1978-2015 NECOFS hindcast fields, thus enabling examination of impacts of climate change and upstream conditions on the region; and 5) provide technical support to couple the proposed biological model with the physical model.

Biological model—To better resolve the key changes in size structure (as a proxy for composition) in the planktonic food web, we will use an intermediate complexity ten-component, size-structured NPZD-type model (Fig. 20). The model was designed to resolve the primary energy flows within the planktonic food web (Stock and Dunne 2010) and is a distilled, regionally tailored version of the Carbon, Ocean Biogeochemistry, and Lower Trophics (COBALT) model originally developed for the global Earth System Model (Stock et al. 2014). The model compartments represent a core set of functional groups with rudimentary size differentiation common in many ecosystem models. A Monod growth model is used for nutrient-limited growth of phytoplankton and light dependence is modeled according to Geider et al. (1997), allowing for variable chlorophyll:carbon. Zooplankton have a Holling type II response for a single prey type and are assumed to engage in abundance-based switching when multiple prey types are available. The primary difference between small and large phytoplankton is an order of magnitude difference in half-saturation constants for nutrient uptake. Small zooplankton are characteristic of protozoa, medium-sized zooplankton represent small- to medium-bodied copepods, and large zooplankton reflect a large copepod/euphausid group. The model has been calibrated to capture cross-ecosystem differences in production through mesozooplankton (Stock et al. 2014), as well as for regional patterns in phytoplankton bloom dynamics (Song et al. 2011). While we will not explicitly resolve detailed benthic components, we will enhance the biological model to represent benthic-pelagic coupling at the water-sediment interface following Fennel et al. (2006). To do this, we will add a sediment component for a relatively simple representation of benthic mineralization processes. The remineralization of deposited organic matter in the upper part of the sediment will be formulated as a bottom boundary condition in the pelagic model, allowing flux of recycled nutrients to the water column. This approach, deemed to be of intermediate complexity in a hierarchy of benthic-pelagic coupling formulations (Soetaert et al. 2000), is effective in representing the nitrogen cycling processes in the water column and organic matter remineralization at the water-sediment interface, in a way that explicitly accounts for sediment denitrification (Fennel et al. 2006). A fully resolved benthic model is beyond the scope of Phase I, but could be developed by including more benthic food web interactions in the model through separately funded projects or in later LTER phases.

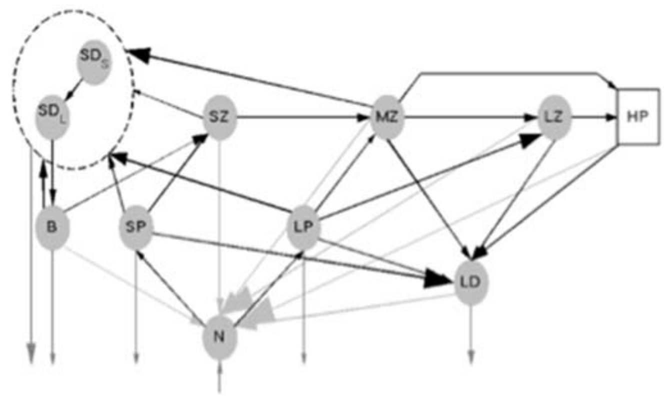

Fig. 20. Ecosystem model structure. There are ten state variables (gray circles): SP = small phytoplankton, LP = large phytoplankton, SZ= small zooplankton, MZ = medium size zooplankton, LZ = large zooplankton, B = bacteria, SD_S = labile small detritus, SD_L = semi-labile large detritus, and N = limiting nutrient. HP = higher predators that are not explicitly resolved. More details can be found in Stock and Dunne (2010).

The biological model will be driven by hourly output fields from FVCOM. The two successive hourly physical fields will be linearly interpolated to the biological time step, and the derived fields will fulfill the continuity equation to ensure volume conservation. Similar to most of the large-scale marine ecosystem models, we will initialize the model with a combination of the most up-to-date global scale climatological data for nutrients (the 2013 gridded World Ocean Atlas) and the shelf-scale nutrient information available for the NES (see Table 2). High-resolution regional nutrient climatologies under development at NODC will be incorporated as they become available. Other variables (e.g., phytoplankton, zooplankton and detritus) will be allowed to dynamically evolve from low initial values to states consistent with nutrients and physical forcing over a model spinup of ~5-10 years (until quasi-equilibrium). Dynamic boundary conditions for nutrients will be derived from observed relationships between slope water properties and nutrient content (Townsend et al. 2006; Townsend et al. 2010). Model validation will include a critical assessment of climatological and interannual variations in seasonal and spatial patterns of the model-computed and observed Chl a and plankton biomass and size composition.

1.7.10 Population models

We plan to investigate the population dynamics of key species with targeted modeling approaches, such as trait-based models that utilize high-resolution observations to characterize phytoplankton physiology. We have previously developed such models and used them to study drivers of growth of *Synechococcus* at MVCO (Sosik et al. 2003; Hunter-Cevera et al. 2014). We intend to extend these models to other species that typify the NES. While these models will not be explicitly linked with realistic simulations of the physical environment, they can provide insight into the mechanisms by which key species respond to environmental factors, without the confounding effects of aggregate properties that might reflect compensatory responses of multiple species (e.g., Fig. 2a).

To study *Synechococcus*, we constructed a matrix population model, an approach that has proven useful across a wide variety of taxa (Caswell 2001). With descriptions of how cell growth depends on light and cell division depends on size, the model predicts how cell size distribution changes within a population. Model parameters are estimated by fitting the model (using likelihood-based techniques) to a time-series of size distributions collected over the course of a day. The fitted model can then be used to estimate cell division rate (independent of grazing and other losses). Hunter-Cevera et al. (2014) verified that this approach accurately estimates division rate in laboratory cultures and in comparison to results from dilution series experiments with natural *Synechococcus* populations. We have already applied this approach at MVCO to diagnose decadal-scale responses of *Synechococcus* bloom dynamics to climate variables (Hunter-Cevera et al. 2016). We propose to extend those analyses to test specific hypotheses about physiological and ecological factors promoting earlier and more prolonged picophytoplankton blooms under ocean warming scenarios.

This structured-population modeling approach is general enough to use for many kinds of phytoplankton. It has recently been adopted by others to study dinoflagellates (Dugenne et al. 2014) and *Prochlorococcus* (Ribalet et al. 2015). For NES-LTER objectives, we will work to extend the model to a representative winter-blooming diatom species at MVCO (e.g., *Guinardia delicatula*, Fig. 4) where high frequency imaging of cell properties will be available for parameterizing the model.

While initial plans for population-scale modeling will be focused on phytoplankton, as possible, we will explore expansion of these and similar approaches to important zooplankton species (e.g., *Calanus finmarchicus*). In addition, collaborations with partners at NMFS will be developed to incorporate work on population models for forage fish, which include representations of predator-prey interactions, reproduction, recruitment, and development (Richardson et al. 2011b). Ultimately, findings from strategic population models like these will be used to improve process representations and parameterization in the food web models used for large-scale simulations and to provide mechanistic insight into responses of species found to play critical roles in structuring NES food webs.

Table 2. Summary of proposed NES-LTER observations by major category and primary LTER core area(s); biological observations include both compositional and aggregate properties across a range of space/time scales, as indicated by primary sampling mode. "Surveys' refers to the quarterly LTER transect cruises, LTER-enhanced EcoMon cruises, and monthly LTER-dedicated MVCO cruises.

Physical oceanographic, meteorological, optical, chemical observations (primary core areas 3, 4, 5)		
Variable	Method or sensor	Sampling mode
Temperature, Salinity	CTD	surveys, MVCO & OOI continuous
Current velocity	ADCP	surveys, MVCO & OOI continuous
Surface currents	CODAR	remote sensing
Surface waves, Reynolds stress	SonTek/YSI ADV	MVCO & OOI continuous
Incident radiation	radiometers	surveys, MVCO & OOI continuous
Wind velocity & stress	sonic anemometer	MVCO & OOI continuous
Air temperature, relative humidity	Vaisala VaiPTU	MVCO & OOI continuous
Radiance/irradiance (sun, sky, sea)	CIMEL SeaPRISM sun photometer	MVCO continuous
Absorption, attenuation	WETLabs ac-9	OOI continuous
Absorption (particles, CDOM)	spectrophotometry	transect surveys, MVCO discrete
CDOM fluorescence	WETLabs WETStar	MVCO continuous
Backscattering	HOBILabs Hydroscat-6	MVCO continuous
Nutrients	Satlantic ISUS (NO_3 only)	OOI continuous
	autoanalyzer	surveys, MVCO discrete
POC/PON	CHN analyzer	transect surveys, MVCO discrete

Abundance, biomass, and community composition by trophic level (primary core areas 1, 2, 3)			
Trophic category	Variable type	Method	Sampling mode(s)
Bacteria	abundance, biomass	flow cytometry	selected surveys, MVCO discrete
	composition	high throughput sequencing	selected surveys, MVCO discrete
Phytoplankton	abundance, biomass	chl fluorescence (in vivo)	surveys, MVCO & OOI contin.
		chl extraction	surveys, MVCO discrete
		MODIS/VIIRS ocean color	remote sensing
	abundance, biomass, composition	flow cytometry / imaging	surveys, MVCO continuous
		microscopy and sequencing	select surveys, MVCO discrete
Micro-zooplankton	abund., biomass, compos.	imaging flow cytometry	surveys, MVCO continuous
	composition	high throughput sequencing	select surveys, MVCO discrete
Meso- & macro-zooplankton	abund., biomass, compos.	multi-frequency acoustics	surveys
	abund., biomass, compos.	net tows / microscopy	surveys, MVCO discrete
		imaging	surveys, MVCO continuous
	composition	bar-coding	select surveys, MVCO discrete
Small pelagic fish	abund., biomass	net tows	trawl surveys
Groundfish	abund., biomass, compos.	trawls	trawl surveys

Rate processes and trophic analyses (primary core areas 1, 2, 3, 4)			
Trophic category	Variable type	Method	Sampling mode(s)
Bacteria	Bacterial production	^{3}H-leucine incubations	select surveys, select MVCO discrete
Phytoplankton	NCP	oxygen/argon	surveys contin. & discrete, MVCO discrete
	GPP	triple oxygen isotopes	surveys, MVCO discrete
	NPP	^{14}C incubations	select surveys, select MVCO discrete
	growth rate (bulk)	dilution experiments	select surveys, select MVCO discrete
	growth rate (by taxa)	flow cytometry / trait analysis	MVCO continuous
	NPP	MODIS/VIIRS	remote sensing
Microzooplankton	grazing rate	dilution experiments	select surveys, select MVCO discrete
Meso- & macro-zooplankton	food web base & trophic level	stable isotope analysis	select surveys, select MVCO discrete
Small pelagic fish	diet & trophic level	stable isotopes, gut contents	trawl surveys
Groundfish	diet	gut contents	trawl surveys

1.8 LTER Core Research Areas – Integration and Synthesis

The NES-LTER strategy will integrate the five cross-cutting LTER core research areas (Sections 1.8.1-1.8.5) utilizing in situ observations, process studies, and data-assimilative modeling. The NES-LTER will provide a comprehensive and co-located set of measurements, held in common with the LTER network, of the environmental conditions, biological stocks, and rates of change that characterize the NES ecosystem throughout all seasons over multiple years, capturing intra- and interannual variability. Our ecosystem characterization measurements will capture events at a range of space and time scales— from sub-centimeter and minutes to kilometers and annual events—and will link small-scale processes with their larger scale ecosystem ramifications. We will measure critical aspects of compositional and aggregate variability with environmental and climate context, thus providing the basis to address our guiding questions that are rooted in theoretical ecology (Fig. 2):

Q1: *What are the main factors controlling spatial and temporal patterns of plankton species composition and biological production?* Required spatial and temporal patterns will be determined through integration of core areas 1 and 2, with knowledge about controlling factors determined principally through activities associated with core areas 4 and 5. (See details in following paragraphs.)

Q2: *How is variability in the feeding, condition, and distribution of pelagic forage fish linked to interannual variability and multi-year trends in plankton size structure and species composition and the ratio of export to total primary production?* Required variability and trends will be assessed principally in core area 2 activities (see below), and then integrated with findings associated with *Q1* and core area 3.

Q3: *Is the NES ecosystem (and the services it provides) vulnerable to dramatic transformation in the face of rapid climate-induced environmental changes? Or does the diversity of species confer resilience, providing a buffer against dramatic changes in overall productivity via shifts in species composition?* Initial hypotheses will be evaluated for evidence that relationships between compositional variability (in plankton and fish) and aggregate variability (e.g., in biomass and export production) are either compensational or synchronous, requiring information principally from core areas 1, 2, and 3.

1.8.1 Core area 1: Patterns and controls of primary production

Rates and patterns of primary production and their response to environmental conditions and disturbances are a fundamental and structuring component of the NES-LTER. Primary production will be measured through discrete incubation experiments (^{14}C uptake) on seasonal process cruises that transect the shelf and on selected cruises to MVCO. Primary production will be evaluated as a function of potential drivers, including nutrients and irradiance. Complementary approaches to assess primary production, specifically triple O_2 measurements of GPP, and NCP through O_2/Ar ratios, will provide higher spatial coverage on all cruises and thus provide a much more complete view of the spatial and temporal distribution in primary production (see Section 1.7.6). This coverage is critical given the highly dynamic NES environment. Furthermore, in conjunction with NMFS collaborators (see letter from K. Hyde in Supplementary Documents), incorporation of NPP estimates from satellite-based observations will provide regional coverage at weekly to monthly intervals. The proposed set of complementary and, at times, overlapping approaches will provide a unique data set to (a) explore the different facets of primary production related to photosynthesis, respiration, and export and (b) quantify variability in estimates as a function of methodology—an important component of distinguishing natural variability and responses to environmental change from methodologically derived variability.

1.8.2 Core area 2: Spatial and temporal population dynamics and food web interactions

The NES-LTER includes empirical and modeling-based food web studies spanning organisms from microbial photo- and heterotrophs to fish, including bacteria, phytoplankton, zooplankton, and small pelagic fishes. Our work will combine high-resolution, high-frequency observations of marine microbes, through in situ technology (flow cytometry and imaging) and genetic tools to quantify abundance, biomass, and diversity, including changes in response to environmental conditions. Abundance and diversity of meso- and macrozooplankton and pelagic fish will be assessed from net tows, DNA barcoding, and microscopy/imaging. Moreover, we will utilize dedicated incubation experiments to assess trophic interactions among marine microbes <200 µm by measuring rates of herbivorous predation as a function of environmental conditions and irradiance. Estimates from bulk changes in Chl a will be complemented by flow cytometric, imaging, and microscope analyses to reveal species-specific patterns in phytoplankton growth and grazing by zooplankton. These concurrent measurements of phytoplankton loss and growth will provide estimates of NPP at the compositional scale to complement the aggregate estimates acquired through the approaches summarized in Section 1.8.1. Gut content and stable isotope analysis of the six species of dominant small pelagic fishes will yield information on the specific trophic pathways from zooplankton to the important ‘forage fish’ species in the region, which represent a critical link between planktonic production and higher trophic levels in the NES ecosystem. Stable isotope analysis of size fractions and key taxa of zooplankton will elucidate the variability in energy flow from the plankton to forage fish, and highlight how trophic pathways not only change with time and space but also alter consumer-specific foraging behaviors and prey preferences. To diagnose population dynamics for key species, we will use trait-based matrix models such as those that utilize high resolution observations to characterize phytoplankton physiology (Hunter-Cevera et al. 2014). The assessments of food web structure and trophic interactions will be critical to parameterizing patterns and responses of trophic structure in large-scale simulations that integrate across the ecosystem and resolve responses of processes to environmental change and disturbance. Results from our in-depth examination of planktonic processes will be related to the abundances, diets, and stable isotope signatures of forage fish, as well as the feeding dynamics of upper trophic levels and the resulting community-wide properties of food web architecture, including food chain length, link density, and connectance (O'Gorman et al. 2012). Together, these analyses will provide a window into the mechanisms by which climate regime shifts on the NES impact fisheries productivity.

1.8.3 Core area 3: Patterns and controls of organic matter accumulation and decomposition

Measurements of primary production, biomass by trophic level, and trophic interactions will be used with numerical ecosystem models (fully coupled to realistic physics) to provide a comprehensive framework for diagnosing the drivers of change in organic matter pools, including export production to the benthos and higher trophic levels in the pelagic. Estimates of the size and group-specific biomass of plankton and fish, complemented with aggregate particulate organic carbon and nitrogen analysis, will provide compositional (group- and trophic-level-specific) estimates of organic matter pools. These measurements will be routinely made on cruises to provide a detailed assessment of environmental, climate, and biological drivers of organic matter transformation to and from various pools. The NCP contribution to the dissolved organic matter pool will be estimated from the dissolved tracer NCP budget. Additionally, dissolved pool fluxes will be estimated on regional scales with remote sensing algorithms (Mannino et al. 2016). Predictive modeling that includes state variables for dissolved matter and components of an intermediate-complexity size-structured planktonic food web (Stock and Dunne 2010; Stock et al. 2014) will be used to resolve how organic matter transformations are linked to compositional variability and primary energy flows, and how these in turn respond to physical forcing and patterns of disturbance.

1.8.4 Core area 4: Patterns of inorganic inputs and movements of nutrients

A similar strategy that combines observations and the coupled physical-biological model will be used to characterize nutrients and their transformations. In this case, the multi-scale sampling approach will allow us to examine nutrient dynamics across the NES and, in particular, determine how large-scale patterns of advection (and variation in upstream source waters) and exchange across the shelf break front influence the spatial and temporal dynamics of nutrient fields across our focal transect. Survey cruises throughout the NES-LTER area, cross-shelf transects, and MVCO cruises will include discrete measurements of macronutrients (NO_3, NO_2, NH_4, $Si(OH)_4$, PO_4). Additional in situ measurements of NO_3 are available from the OOI Pioneer array. As new sensor technologies advance, we will actively pursue incorporating more continuous nutrient measurements into the NES-LTER observing program. On transect cruises with process studies, the effect of nutrient concentrations on trophic interactions will be measured through macronutrient additions to incubation experiments that quantify growth and grazing rates. The distributions, sources, sinks, and volume transport of inorganic nutrients within the NES-LTER region will be constrained by the coupled physical-biological model. The models will be informed by the suite of physical, meteorological, optical, and chemical data from sensors throughout the region on cruises, weather and wave buoys, OOI, and MVCO (Table 1, Table 2).

1.8.5 Core area 5: Patterns and frequency of disturbance

The NES-LTER is located in a temperate region that spans tremendous environmental gradients from subtropical conditions in summer to sub-polar in winter. It thus provides immediate opportunities to characterize ecosystem processes as they respond to environmental conditions, including disturbances from extreme weather events to interannual variations in temperature and stratification, and ultimately extending to longer-term changes linked to climate processes. Because of the highly dynamic nature of the NES, we will be able to quantify patterns in physical disturbance, the ways they impact nutrients, and the resulting compositional and aggregate ecological responses on a range of spatial and temporal scales. Special attention will be paid to years with extreme climate signals (e.g., warming, freshening), which will yield insight for future scenarios that match long-term projections. Regional-scale observing system components and remote sensing (Table 1) will be used to constrain patterns of advection, frontal dynamics, cross-shelf exchange, and timing and strength of stratification across the NES. The quarterly LTER-enhanced EcoMon surveys will allow assessment of seasonality and processes over multiple years and broad spatial scales. At the same time, the NES-LTER capitalizes on high-resolution, in situ technology at MVCO and OOI that permits observations on the spatial and temporal scales relevant to marine microbes (~days), but also extending long enough (months to years) to capture many events and low-frequency patterns. Low-frequency changes may be critical to ecosystem structure and function, but, in high-turnover, microbial-dominated systems, they can only be discerned with the type of high-frequency long-term observations that the NES-LTER will support. As is important for all core areas of the NES-LTER strategy, the coupled physical-biological modeling approach (which includes nesting in a global ocean model) will span high-frequency local scales, interannual and regional scales, and up to decadal scales and basin-scale forcing. Taken together these strategies align with our conceptual and theoretical framework (Section 1.2) that hinges on being able to quantify and understand low frequency patterns and responses, in a way that begins with and ultimately depends upon appropriately resolving high-frequency variability and mechanistic process-level understanding (Fig. 2, Fig. 3).

1.8.6 Cross-LTER synthesis

As the NES-LTER matures, we will actively engage in cross-system syntheses within the broader LTER network. While the nature of these efforts could follow many directions, as an initial focus, we would like to engage the CCE-LTER and PAL-LTER investigators in a comparison of the ways in which compositional and aggregate ecosystem variability are linked in marine pelagic systems. While they occupy very different oceanographic regimes, with associated differences in patterns and frequency of disturbance, the conceptual frameworks for NES-LTER, CCE-LTER and PAL-LTER are each focused around understanding patterns of change in plankton community composition and how those changes propagate to influence food web structure, function, and aggregate properties, such as energy transfer to higher trophic levels.

A fundamental challenge in marine ecology is to uncover underlying "rules" for how pelagic communities organize and connect to ecosystem function, rules which are general enough that they can be used to understand and predict responses to natural and anthropogenic-induced stressors in the coming decades. We can build from existing paradigms (for instance, those linking shifts in size structure to changes in primary production and export), but comprehensive data sets such as those available through LTER programs can provide a unique opportunity to evaluate findings and test ideas across systems with contrasting physical regimes and scales of spatial and temporal variation if those contrasts exist at the various LTER sites. The NES—a wide continental shelf, driven by advective processes, forced by strong seasonality in temperature, supporting a unique and dynamic biological community, and adjacent to the largest and most densely populated metropolitan area in the United States—will provide just such a valuable contrast and complement existing LTER programs.

2 BROADER IMPACTS, EDUCATION AND OUTREACH

The NES-LTER overall broader impacts strategy has two foci: (1) close collaboration and data dissemination with the NOAA Northeast Fisheries Science Center (NEFSC) to support their efforts in multispecies, ecosystem-based management on the NES, and (2) an education/outreach plan that will provide opportunities to a broad range of learners. We will address important societal goals including improving knowledge of ecosystem services that benefit human well-being and increasing literacy in science, technology, engineering, and mathematics (STEM) principles. Both foci are described below.

2.1 Ecosystem services of the NES Large Marine Ecosystem

We will develop a close collaboration with partners at NEFSC to incorporate relevant LTER observations into their Integrated Ecosystem Assessment (IEA) program that assists with ecosystem-based management in the northwest Atlantic Ocean. The NES-LTER is focused on a region that has experienced the greatest warming in the past decade (Saba et al. 2015), with implications for many of the ecosystem services important for humans and society. Ecosystem services may be grouped into four main categories: supporting, provisioning, regulating, and cultural (Millennium Ecosystem Assessment 2005). Our LTER research will touch on each of these including (1) improving knowledge of *supporting* services (e.g., primary production, nutrient cycling); (2) supporting fisheries as a *provisioning* service (i.e., food for humans); (3) improving knowledge of *regulating* services such as climate regulation; and (4) enhancing *cultural* services (e.g., for education as described below). We will collaborate directly with NOAA's NEFSC which has been examining the changing spatial distributions and productivity of fish and other species over long time periods, dating back decades in the NES Large Marine Ecosystem (e.g., Nye et al. 2009; Bell et al. 2014). We propose to incorporate our LTER data (e.g., new observations on phytoplankton, NCP, and fish diets) into the regularly communicated Ecosystem Advisories and Status Reports (e.g., NOAA 2016). These reports are used in the IEA process that includes scientists, policy makers, and other stakeholders (Levin et al. 2009). These shared observations will also support food web and end-to-end modeling being conducted as part of the multispecies, ecosystem-based management approach implemented at NEFSC.

2.2 Education and public outreach

The NES-LTER Education/Public Outreach plan has three main components: (1) direct engagement of undergraduate and graduate students and postdoctoral researchers in LTER research; (2) an LTER Schoolyard program that engages Middle and High School students and teachers; and (3) public outreach through NOAA’s international Science On a Sphere (SOS) Users Network. Our goals are aligned with growing efforts to incorporate publicly available Earth and life science data into formal and informal educational activities to advance STEM literacy (e.g., Bader et al. 2016).

2.2.1 Undergraduate, graduate, and postdoctoral researchers

We will involve undergraduate and graduate students and postdoctoral researchers directly in the LTER research, and they will gain valuable training in not only field, lab, data management, and analytical skills, but also in collaborating in a multi-investigator/multi-disciplinary project. Over the course of the grant period, we will offer research experiences for undergraduates (REUs), including 12 sponsored by the LTER at WHOI, 12 at the University of Rhode Island (URI), and 18 at Wellesley College. The LTER REUs at WHOI will be coordinated with the Woods Hole Partnership in Education Program (PEP; a multi-institutional effort to promote diversity in the Woods Hole science community) and WHOI’s Summer Student Fellow (SSF) program. At URI, undergraduates will be incorporated into the NSF-sponsored summer undergraduate research fellowship in Oceanography (SURFO), a program that has been ongoing for 32 years and includes research opportunities, career mentoring, and graduate school preparation. At Wellesley, at least two undergraduates each summer will be mentored as part of Wellesley’s vibrant summer research program, a program which is typically composed of 120 female students, ~35% of which are under-represented minorities and first generation college students. Additionally, one sophomore will be mentored during the academic year at Wellesley through the Sophomore Early Research Program, a program for low income students where they receive work-study money for conducting research in a faculty member’s lab during their sophomore year. Furthermore, coincident with the start of this project, Wellesley College is hosting its first STEM POSSE—a set of students that might be missed by traditional admissions criteria and who are often under-represented minorities and/or first generation college students (Posse 2016). One of these POSSE students will work on this project, allowing a student from a non-traditional background to get firsthand scientific research and to, in turn, share her experiences with her POSSE peers and friends and family. Graduate students are proposed at WHOI and the University of Massachusetts, Dartmouth, in particular to work with co-PIs Llopiz and Chen in synthesis of observational and modeling data. Postdoctoral researchers are proposed at WHOI and URI, in particular to work with co-PIs Ji (coupled modeling development and implementation), Menden-Deuer (plankton rates, processes and transformations), and Rynearson (plankton population dynamics/ genetic diversity) (see Postdoctoral Mentoring Plan).

2.2.2 LTER Schoolyard

Our proposed LTER Schoolyard program focuses on Middle (MS) and High School (HS) curricula supporting introductory to advanced data analysis, e.g., change over time, ecological similarities/differences in marine vs. terrestrial systems, making claims supported by evidence and reasoning. We will engage teachers from the region (i.e., Massachusetts, Rhode Island) to participate in professional development (PD) workshops and in research experiences either on board cruises or in the labs of participating scientists. We will engage the students of these teachers in curriculum use, classroom research, and using data/visuals on laptop or tablet-based applications (adapting to technology available in different schools). Components of the Schoolyard program *numbered in italics below*, will be led by Annette Brickley, Science Education Consultant. Brickley was the Education Director of the Ocean Explorium in New Bedford, MA, has an M.S. in Oceanography, six years of classroom teaching experience, and 12 years in science outreach, professional development, and instructional design. Brickley has worked with co-PI Beaulieu on projects to advance ocean literacy (Beaulieu et al. 2015b).

Curriculum content and a framework for student and teacher research experiences will be developed and aligned to Next Generation Science Standards (NGSS) including Disciplinary Core Ideas and Science and Engineering Practices and MA/RI standards for both MS and HS. *(1) Teacher PD* workshops will be designed integrating LTER research, field sites locally accessible to the teachers, and specific needs of the cohort based on their student populations. Teacher PD will consist of two or three local meetings each year led by Brickley to support student data analysis, further research question development, curriculum exchange, and vertical teaming (to provide continuity for students as they move up grade levels). Teacher PD will focus on teachers from schools in Bristol County, MA, including the city of New Bedford, as part of our efforts to broaden participation. New Bedford has a diverse population, with a greater proportion of "Hispanic or Latino," "American Indian," and "Two or more races" than average in Massachusetts (U.S. Department of Commerce 2016). In 2013-2014, 76% of the students in public schools in New Bedford were classified as low-income as compared to 38% for the state (Massachusetts Department of Elementary and Secondary Education, 2014). Schools that have already indicated interest in the program include Our Sisters School in New Bedford, a tuition-free independent MS for girls from low-income families (see Letter from Jocelyn Mitchell), Global Learning Charter Public School in New Bedford, and Fairhaven HS. Co-PI Chen also has a relationship with SeaLab, a marine science studies program funded through the New Bedford Public Schools (mainly grades 5-8).

Additional teacher PD will be conducted in coordination with the Woods Hole Science and Technology Education Partnership (WHSTEP) for schools in the towns of Falmouth, Bourne, and Mashpee. As a member of the New England Ocean Science Education Collaborative (NEOSEC), WHSTEP will facilitate our connection to teachers in other school systems in MA and RI. *(2) Research experiences for teachers (RET)* will include teacher-at-sea opportunities, to participate as a volunteer and contribute content for a blog on an LTER transect cruise (for students to follow along back at class, but also for public outreach promoted through WHOI's Information Office including social media). *(3) Classroom experiences for students* of those teachers in the PD and RET will include curriculum and research including direct interaction with scientists with remote (e.g., Skype) or in-person classroom visits. We anticipate engaging 8–18 teachers per year, each with 20–60 students. We note that New Bedford is also conveniently located in the center of where the NES LTER co-PIs are distributed, to facilitate the opportunity for co-PIs to visit classrooms. Curricula will include data sets created for the Science On a Sphere® and formatted for virtual globes, and use of the SOS Explorer (SOSx) Lite virtual globe in the classroom (described below). *(4)* Student groups who carry out a full research project during the academic year will earn a full day *field trip* to Woods Hole. The field trip will include the WHOI Visitors and Exhibit Centers, lab experience/tours, and NOAA's Woods Hole Science Aquarium. As a unique outcome of our Schoolyard program, in culmination of the long-term student research experiences, teachers will work with students to write up and publish their work in the *Journal of Emerging Investigators*. Brickley will attend National Marine Education Association Conferences to share the curriculum and this final outcome of student/teacher research.

2.2.3 Public outreach with the Science On a Sphere

Fig. 21. NOAA's Science On a Sphere® (SOS) is a digital globe six-feet in diameter, often on display in an auditorium for public audiences in more than 100 museums and science institutions around the world. (Photo by W. von Dauster).

An important component of our education/public outreach efforts will be creating new data sets and live programs for NOAA's Science On a Sphere® (SOS) Users Network. The SOS is a room-sized, digital globe often on display in its own auditorium for docent-led presentations to public audiences of stories incorporating geo-referenced datasets **(**Fig. 21**)**. The SOS is used at over 100 science centers in more than 20 countries around the world, including 2 current (Discovery Museum and Planetarium, Bridgeport, CT; St. Paul's School, Concord, NH) and 1 planned (Buttonwood Park Zoo, New Bedford, MA) SOS facilities in New England. Our new content can be formatted for other spherical display systems and virtual globes (e.g., Magic Planet, Google Earth). The downloadable SOSx Lite virtual globe allows access to a portion of the SOS data catalog without having to go to an SOS facility. Beaulieu and Brickley have used the SOS in other projects in which content was created to advance public knowledge of ocean literacy principles (Beaulieu et al. 2015b). We will use data from the NES-LTER along with data from other LTER sites, and other data in the NOAA SOS data catalog, to build stories relevant to NGSS in the Life Sciences including LS2 Disciplinary Core Idea "Ecosystems: Interactions, Energy, and Dynamics." NOAA's SOS Program has requested content development aligned with NGSS (see Letter from H. Peddicord). We will improve our new content in conjunction with teachers and students interacting with LTER data as part of our Schoolyard program (described above).

3 RESULTS FROM PRIOR NSF SUPPORT

Note: publications in section D, marked with superscript symbol for each project (*,#,@,&,%,^, α, β).

[*]**Beaulieu, S.E.** NSF Geoscience Education #1202977 ($456,699; 7/2012-6/2015). A "Global Viewport" for Virtual Exploration of Deep-sea Vents: Using Spherical Displays to Advance Public Literacy in Earth System Science. **Intellectual merit.** From the global locations of deep-sea vents, imagery from deep-diving vehicles, and other datasets in the NOAA SOS catalog, we created two narratives ("Life Without Sunlight" and "Smoke and Fire Underwater") to educate and excite the public about biological and geophysical processes and exploration in the deep ocean. Both narratives led to perceived learning of ocean literacy principles. Four publications resulted from this project to date. **Broader Impacts.** We delivered new datasets, movies, playlists, and scripts to the NOAA SOS Users Network, which includes over 100 SOS facilities in more than 20 countries. In addition to the NOAA SOS data catalog, our datasets and movies are available freely from the Woods Hole Open Access Server for other spherical display platforms. Additional evidence of research products and their availability includes the InterRidge Vents Database Versions 2.1 and 3.3.

[#]**Chen, C.**, **Ji, R.**, Record, N. Runge, J., Salisbury, J.: OCE-1459133 ($425,891; 4/2015-3/2018) *Collaborative Research: Mechanisms Supporting Persistence of a Key Plankton Species During Climate Change on the Northwest Atlantic Continental Shelf.* **Intellectual Merit**: This research develops a process modeling approach to advance a hypothesis that takes into account regional and mesoscale interaction between life history, bathymetry and circulation in order to understand planktonic species distribution shifts. **Broader Impacts**: This research will provide mechanistic understanding of the processes controlling the abundance of *C. finmarchicus* in the GoM as well as observations and modeling tools to assess and predict its present and future status. To date, this project has generated one publication and 5 conference presentations in national and international meetings.

[@]**Lentz, S. J.** OCE-1154575 ($709,692; 2/15/2012-1/31/2015) *Circulation and transport in Hudson Shelf Valley.* **Intellectual Merit:** Hudson Shelf Valley extends across the Middle Atlantic Bight shelf and provides a conduit for cross-shelf exchange via along-valley currents of 0.5 m s^{-1} or more. Observations indicate that the vertical structure and strength of the along-valley current depends on both the wind stress magnitude and direction and changes in near-bottom stratification and bottom boundary layer thickness. **Broader Impacts:** A better understanding of shelf valley dynamics provides the physical basis for studies of biological productivity and contaminant/larval dispersal associated with the strong cross-shelf transport in these features. This project resulted in 3 publications.

Llopiz, J.K. OCE-1325451 OCE-RIG ($99,809; 9/1/2013-8/31/2016), *Novel Approaches to Better Understanding the Trophic Role of Small Pelagic Fishes and their Critical Link Between the Plankton and Higher Trophic Levels*. **Intellectual Merit**: This ongoing study takes a novel, multifaceted approach to understanding the important trophic link that forage fish represent between zooplankton and higher trophic levels on the NE US continental shelf using microscopic, stable isotope, and DNA barcoding techniques. **Broader Impacts**: The work is centered on the prominent role that current and recent undergraduates from underrepresented groups will play on the cruises and in the lab. Two presentations at a national conference have been made. No publications yet.

[&]**Menden-Deuer, S.** NSF OCE-0826205 ($600,000; 9/01/2008-09/01/2011). *Deciphering Planktonic Predator-prey Interactions: A Mechanistic Approach*. **Intellectual merit**: This project quantified the effects of protistan movement and foraging behaviors on plankton population growth and grazing rates and discovered novel behaviors with ramifications for food web dynamics. **Broader Impacts**: Sixteen publications (12 student/post-doc 1st authors); 41 talks (13 invited); four theses (3 MSc; 1 PhD). Large public engagement events, such as at the sailing races in Newport, RI that reached >100,000 visitors and international coverage from NPR, CBC, Scientific American, AAAS and the NSF home page.

[%]Caswell, H. Jenouvrier, S. and **Neubert, M. G.** DEB-1257545 ($499,805; 5/01/2013 – 4/30/ 2017). *The Demography and Dynamics of Heterogeneous Populations*. **Intellectual Merit:** We are studying the dynamics of heterogeneous populations by developing models that incorporate both observed differences among individuals (e.g., age or size) and unobserved differences (e.g., frailty or quality). The project has produced 15 peer reviewed publications to date. **Broader Impacts:** One PhD student participated in the research on this project. PIs presented several workshops, at national and international meetings.

[^]**Rynearson, T.A.** NSF-OCE 0727227 ($852,094; 10/2007-9/2013) *Connecting Local, Regional and Global Scales of Gene Flow in Planktonic Marine Diatoms*. **Intellectual Merit**: Genetic diversity and connectivity among populations can influence a species' ecology, adaptive potential and evolutionary longevity. This research investigated diversity and connectivity of planktonic diatom populations from local to global scales. **Broader Impacts**: Three graduate and 8 undergraduate students and 1 postdoc were supported. Outreach included participation in RI GRRLTech Collective events, the Narragansett Bay Classroom and the National Ocean Science Bowl. This grant resulted in 11 publications.

[α]Olson, R.J., **Sosik, H.M.** OCE-1130140 ($934,340; 9/15/2011-8/31/2016), *Collaborative Research: Enhanced Imaging Flow Cytometry for Plankton Studies via Acoustic Focusing and Emulsion Microfluidics.* **Intellectual Merit:** We have developed and evaluated enhanced capabilities that integrate with the automated imaging-in-flow cytometer Imaging FlowCytobot (IFCB), including 1) acoustic focusing to pre-concentrate particles above the flow cell; 2) physical sorting of imaged cells; and 3) automated live-cell staining for imaging protozoa. To date, the project has resulted in 2 publications, 1 patent application, and >10 national and international presentations. **Broader Impacts:** Research training for two undergraduates, enabling two PhD theses, advancing technologies that enhance the observational capabilities of the ocean sciences community, and outreach through the Zephyr Education Foundation.

[β]**Stanley**, **R**., A. Spivak OCE-1233678 ($786,298; 8/2012 to 7/2016) "*Eutrophication Effects on Sediment Metabolism and Benthic Algal-bacterial Coupling: An Application of Novel Techniques in a LTER Estuary*". **Intellectual Merit:** We probed effects of increased nutrient loading in salt-marsh creeks and ponds and found increased rates of gross primary production but more negative net community production, a shift in active members of microbial communities, and light respiration rates double those of dark, as described in 3 published papers to date. **Broader Impacts**: We mentored 13 female undergraduate students (including under-represented minorities and first generation college students) and one doctoral student, and provided information on managing an important economic resource.

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FACILITIES, EQUIPMENT AND OTHER RESOURCES

WHOI

The Woods Hole Oceanographic Institution (WHOI) is the largest independent, not-for-profit, oceanographic research institution in the world. Founded in 1930 in the village of Woods Hole, Massachusetts, the Institution's facilities have grown to encompass 219 acres of land and waterfront and 58 buildings and laboratories. The paid staff numbers about 900, with more than half involved directly in scientific research. The Institution's higher education programs enroll about 125 students in graduate-level studies and about 35 in undergraduate summer fellowships. A wide range of shop services and facilities are available to WHOI staff including a precision machine shop, carpentry shop, and graphics services.

Instrumentation and observatory access: WHOI operates the Martha's Vineyard Coastal Observatory (MVCO) facility, to which we will have full access for instrument deployments and core environmental data (http://www.whoi.edu/mvco). WHOI operates the 60-foot coastal boat R/V Tioga (https://www.whoi.edu/main/ships/tioga), available for research projects at a fixed day rate. Funds for this boat time (to access the MVCO site, 1.5 h from WHOI) are requested in this proposal. WHOI has complete facilities to support the diving operations needed to deploy and maintain the in situ instrumentation involved in the proposed research.

Sosik and collaborators at WHOI maintain a series of automated submersible flow cytometers (FlowCytobot and Imaging FlowCytobot series), including several Imaging FlowCytobot units optimized for measuring and imaging microplankton. One or more of these instruments will be available for the continued fieldwork at MVCO for the duration of this project (funds requested in the proposal will support an additional Imaging FlowCytobot). In the Sosik laboratory, the PIs will have access to facilities and equipment to support maintenance and evaluation of instruments for the proposed field deployments. These include a wide variety of electrical, optical, electronic equipment and testing devices, including power supplies, function generators, digital oscilloscopes, diode lasers, LEDs, photomultipliers, amplifiers, and PIC microprocessor systems.

Sampling and analytical facilities: In their laboratories and within shared-use institutional resources, the PIs have the facilities required to carry out the proposed work. These include incubators, microscopes equipped for phase contrast, epifluorescence and transmitted light microscopy, high-powered stereomicroscopes, a Beckton-Dickinson FACSCalibur flow cytometer, an Accuri C6 flow cytometer, spectrophotometers, refrigerators, -20°C and -80°C freezers, balances, centrifuges, plankton nets, laminar flow hoods, and fume hoods. Equipment involved in the isolation and amplification of nucleic acids is also available, including microcentrifuges, PCR machines (Applied Biosystems 2720 (96 well format) thermocycler, Bio-Rad C1000 Touch Thermal Cycler for real-time PCR), agarose gel electrophoresis equipment, and an Alpha Innotech imager for gel documentation. At WHOI, there is a Thermofisher 253 Isotope Ratio Mass Spectrometer configured for measuring triple oxygen isotopes and O_2/Ar ratios. The attached automated processing line makes use of a custom-made cryogenic trap, Neslab recirculating chillers, GC column, refrigerated bath, turbomolecular pumps, and mechanical pumps. The entire system is under automated control and can be checked from the internet.

Computing: The Information Management (IM) component of the NES LTER project will be located at WHOI, with the data center for physical storage located at the Quissett Campus. Information Services (IS) support will be provided by the WHOI IS group, with technical specialists in system and database administration and applications programming. The NES LTER Information Manager, Stace Beaulieu, also serves on the WHOI IS advisory team and is coordinator of the Ocean Informatics working group which reports to WHOI's Director of Research. WHOI IS provides a range of free and at-cost services for all WHOI researchers, students, and staff, including desktop, server, and software support. WHOI IS Security provides several functions, including managing firewalls, analyzing network traffic, providing network level antivirus and vulnerability protection, and identity and password management, to ensure that systems are protected by a multilayered defense strategy, while safely allowing outside access to public services. The NES LTER will require multiple servers (although we expect most of these to be virtualized) and multiple net attached storage appliances for high volume and high frequency data. The local repository for NES LTER EML data packages will include at least a file server and scripts to utilize the PASTA Data Package Manager Web Service. This local repository may be integrated with our website (e.g., by adopting a content management system utilized at existing LTER sites) for which we will implement a development and a production site. WHOI IS also provides data backup (on and off site) and disaster recovery services. The WHOI data center is equipped with backup power/cooling and physically secured with electronic locks. Additional support for data curation will be available from specialists at the MBLWHOI Library, in particular for implementing data access through the Woods Hole Open Access Server (WHOAS) and for minting DOIs for data sets.

For routine computing, all PIs have computers and peripherals in their laboratories, including an automated daily back-up system (administered by WHOI IS). Computational infrastructure available in the Sosik laboratory includes three Dell Precision T7500/7600 six core workstations with more than 3TB storage for routine data analysis and access; and, for more demanding image analysis and classification tasks, three Dell R710 PowerEdge servers (rack mounted), each with two 6-core Xeon X5660s 2.8GHz processors, 72 GB of RAM, and 5TB of local disk space. The R710 servers are connected to a BackBlaze Storage Pod with 120TB installed disk storage and to one another via dedicated 10 GigE switch. WHOI has a dedicated high-memory multi-processor server for high throughput sequence data analysis, with 1 TB RAM, and 40 (80 hyperthreaded) processors. We also have access to a shared community computer resource, consisting of a 102 node (1224 processor) cluster, with Infiniband interconnects and both high memory (96 GB RAM) and standard (48 GB RAM) nodes. Server usage is overseen by an institutional user advisory committee, and bioinformatics support is also available. The cluster is in the process of being upgraded for greater analytical speed and capacity, and to include storage space for raw and processed data. Additional computing resources will be made available for this project through WHOI's Information Services department (see in-kind resources described below).

WHOI maintains a site license for MATLAB and the MATLAB toolboxes, which will be used in the proposed research. WHOI's graphic services department offers the expertise in animations, web design, and video processing, including post-production video editing, needed for the outreach activities.

Office: All PIs have their own laboratories equipped with personal computers, office space for students and visitors, meeting space, and all necessary peripherals. Office space and computational resources for graduate students and summer undergraduate fellows will be provided in their labs.

In-kind resources: WHOI will provide a range of in-kind resources to enable the proposed project. The NES-LTER will be administered through WHOI's Center for Ocean, Seafloor and Marine Observing Systems (COSMOS), which currently oversees the operation of MVCO and coordinates WHOI's role in regional ocean observing networks. Administrative Professional support for LTER activities will be provided through the COSMOS office. WHOI will provide sponsorship for summer undergraduate researchers (through the long-running, endowed Summer Student Fellowship program) and resources needed to develop and maintain the NES-LTER data and information system, including computational infrastructure, data storage and server hardware, and support staff (programmers, system administrators) available in WHOI's Information Services group. Additional in-kind support includes access to a range of specialized research facilities.

UNIVERSITY OF RHODE ISLAND

PIs Menden-Deuer & Rynearson are both faculty members at the Graduate School of Oceanography, the University of Rhode Island. They each hold a 9-month state supported faculty position.

PI Menden-Deuer has two adjacent laboratory spaces to allow for separate handling of live experiments and toxin related work. There is a separate facility with independent generator support that houses two 30-ft^3 light and temperature controlled incubators. The laboratory for handling live cultures contains a laminar flow work bench for sterile manipulation of cultures and a Coulter Counter for enumeration and size classification of plankton cultures. Menden-Deuer has three Nikon microscopes: an Eclipse 800 for video and photography, a Diaphot 300 with epifluorescence, and a SMZ-U dissecting scope for isolating live cells. The lab is equipped with standard glass and plasticware for media preparation and culturing live cells. An autoclave is available adjacent to the lab for sterilizing materials. Menden-Deuer maintains an active seagoing operation to study plankton population dynamics in situ and has deckboard incubators along with the necessary hardware to incubate plankton samples under simulated in situ light and temperature conditions. Thus, Menden-Deuer is only requesting minimal supply funds for consumables.

PI Rynearson has three laboratory spaces to allow for separate handling of 1) live cultures, 2) fixatives and DNA stains and 3) general molecular biology reagents and procedures. The laboratory for handling live cultures contains 2 Percival incubators (30 ft^3), a HEPA Class 100 UV laminar flow bench, a Zeiss IM35 inverted microscope with epifluorescence, an Olympus dissecting scope, and standard glass and plasticware for media preparation and culturing live cells. A separate dark room is used for fixatives and DNA stains and includes gel electrophoresis equipment for both agarose and polyacrylamide gels, a Syngene Gbox HR for high-resolution gel imaging and a Nanodrop for quantifying DNA and RNA. A third laboratory space is equipped with instrumentation for standard molecular analysis and includes an Eppendorf EPMotion BioRobot for high throughput liquid handling, 2 x 96-well PCR thermocyclers, refrigerated centrifuges, microcentrifuges, refrigerator, freezer, a -80^{o}C freezer for sample storage, liquid nitrogen dewars and dry shippers, a Millipore Synergy deionized water system, pipettors (both single and multi-channel, manual and electronic), balances and standard glassware and plasticware.

PIs Menden-Deuer and Rynearson have access to 4 walk-in incubators for culturing isolates in the basement of the same building as the labs and access to a separate EPSCOR marine life sciences core facility on the GSO campus (see below).

Computers: PI Menden-Deuer has two ethernet-connected computers available: one Macintosh and a Dell PC using the Linux operating system. Both the PI and students have separate office spaces adjacent to the laboratory. Each office has dedicated computers and a shared laser printer. All computers have multiple software packages to support the proposed analyses. All computers are fully networked with an internal server and T1 connections to the internet. A large format printer is available at the GSO computer facility.

PI Rynearson has five ethernet-connected windows-based computers available for the PI and student in the offices and laboratories along with laser printers. The PCs have multiple software packages for DNA sequence analysis (CLC genomics workbench, PERL, Matlab, Sequencher, DNASTAR Lasergene, ABI PeakScanner, Arlequin, Genepop, Phylip, GeneClass, PCAgen, etc). The Rynearson lab maintains a license to use the CLC server located on the URI main campus. The CLC server includes a bundled high performance hardware package with a 3.75TB RAID-5 Array (6x750GB 7200 RPM Near Line SAS Hard Drives) for permanent storage and 900GB RAID-0 Array (2x450GB 15k RPM SAS Hard Drives) for temporary storage. It also includes fast processors (2 Quad-Core Intel Xeon X5550 CPUs --2.66Ghz, 8MB Cache, 6.40 GT/s QPI, Hyper Threading), lots of onboard memory (48GB 1066MHz DDR3 RAM) with networking (Dual Broadcom NetXtreme II 5709c Gigabit Ethernet interface) and good graphics capacity (Matrox G200, 8MB shared video memory). The CLC Genomics workbench, software tailored for next generation sequence assembly and analysis, is installed over an Oracle Enterprise Linux 5 operating system and so the server and software can be accessed remotely. For data archiving, we have 15 TB RAID 5 network servers that archive and backup data on a weekly basis

Offices: The PIs, post-doc, student and technician offices are adjacent to their respective laboratory spaces.

Major Equipment and Facilities: The University of Rhode Island has excellent facilities and equipment for physiological and genomics work related to aquatic ecosystems. The staffed Center of

Excellence in Marine Life Sciences on the bay camps contains a Satlantic FIRe system for measuring variable fluorescence, a BD Influx sorting flow cytometer, a flowcam (Fluid Imaging), a Turner fluorometer, Lachat nutrient analyzer, a Strategene MX3005P real time PCR machine, a fiber–optic oxygen meter (PreSens), a laminar flow bench, pipettors, thermocyclers, a running seawater facility and 4 walk-in incubators. All are available for use by the PIs and personnel on this project.

The main campus of the University of Rhode Island has excellent facilities and equipment for molecular work related to aquatic ecosystems. URI houses a staffed genomics and sequencing center that contains: an Illumina MiSeq sequencing platform, an Applied Biosystems 3130xl sequencer, two Stratagene MX4000 quantitative PCR systems, a MJ research PCR thermocycler, a refrigerated centrifuge, a DNA SpeedVac, a Zeiss LSM 5 PASCAL confocal imaging system, and Zeiss AxioPlan 2 imaging system, which are available for use by the PIs and personnel on this project.

Both PIs have accounts on the Brown University IBM computer cluster in the Center for Computation and Visualization. The PIs each have 30 TB of storage on this cluster, 16TB of which are unassigned and available to this project. This IBM iDataPlex system contains 206 nodes with dual Intel Xeon 5540 quad-core Nehalem processors and 24 GB of DDR-3 memory. **Large Memory Nodes include** 7 nodes with quad-processor AMD Opteron Shanghai-series processors, 6 nodes with 64GB of memory and one with 128GB. A large variety of ‘omics analysis programs (assembly algorithms, CLC genomics workbench, etc) have been compiled on the cluster.

In-kind support: GSO/URI will contribute in-kind support toward the NES-LTER. We are not permitted to quantify this information in this proposal, but this support comes in several forms: (1) support for 1-2 summer research experiences for undergraduates (SURFO/REU) in each year of the proposal, (2) because both PIs are supported by 9 month institutional salary support they request only minimal salary support as part of this NES-LTER and can devote a greater than requested effort to the NES-LTER, (3) GSO/URI has committed at least 1 5-day cruise aboard the R/V Endeavor to support the LTER work in the vicinity of the Pioneer array or elsewhere as the PIs deem appropriate. GSO/URI recognizes the NES-LTER and is willing to make a substantial, long term commitment in support of the NES-LTER.

UNIVERSITY OF MASSACHUSETTS, DARTMOUTH

The Marine Ecosystem Dynamics Modeling Laboratory (MEDML), University of Massachusetts-Dartmouth is an active research group with focus on 1) the FVCOM development and 2) ocean modeling and 3) ecosystem process studies. MEDML has two permanent laboratory spaces that include offices for research scientists, postdoctoral researchers, research associates, and graduate students. All offices are equipped by Internet, phones, dual-processor workstations and PCs/Macs. The laboratory is equipped by a super performance Linux cluster with three generations of processors (the total number of processors are >1000).

The MEDML has established a sister laboratory at Shanghai Ocean University (SHOU), China, named “Sino-US Joint Innovative Center for Polar Ocean Research (SU- JICPOR).” SHOU has established a super-performance Linux cluster for this US-China joint laboratory. This cluster has more than 150 nodes and a total of 1800 CPU processors. This cluster is equipped with a 1000 TB fast-speed data server. PI Chen serves as Chief Scientist of this laboratory, and MEDML has full authority to access and use it remotely. In 2015, SU-JICPOR purchased a special Internet access service with bandwidth of 500 MB/s and 13 public IP addresses to improve the model data transfer speed from SHOU to UMASSD.

NECOFS forecast and hindcast assimilation experiments are made using the MEDML Linux cluster. The hindcast assimilation experiment of Global-FVCOM is made using the SHOU super-performance cluster, which provide the boundary condition for NECOFS’s hindcast simulation.

MEDML/SMAST-UMASSD administers the THREDDS server that allows the public to display and download the model data from the Northeast Coastal Ocean Forecast System (NECOFS). The model output archive is stored on a high-performance Linux cluster server with auto-backup in two different systems and disaster recovery.

WELLESLEY COLLEGE

Sampling and Analytical Facilities: PI Stanley is an assistant professor at Wellesley College. Her laboratory has two field-deployable equilibrator mass spectrometers, configured for measuring a suite of noble gas mole ratios. The systems contain Hiden or Pfeiffer quadrupole mass spectrometers, Agilent compact pumping stations with turbomolecular pumps, VICI switching valves for automated calibration, hot and cold zirconium-iron-vanadaium getters, Membrana Extra-Flow equilibrator cartridge, and an assortment of gear pumps, flow meters, filters, fused silica capillary, and tubing. The instruments measure ratios of the noble gases (Ne, Ar, Kr and Xe) in air or water depending on the position of the VICI switching valve. Water (from a tank or an underway system of a ship or a coastal embayment) is pumped through the Membrane Extra-Flow where the gas equilibrates with the headspace in the cartridge. In order to aid equilibration, a small pump recirculates the air in the headspace through two drying cartridges. A 0.05 mm ID fused silica capillary carries gas from the headspace of the cartridge, or from the air directly, through the getters and into the QMS. No carrier gas is used since the presence of other gases in the QMS is minimized in order to prevent competition of ions within the QMS. A system similar to these but without the getters will be used for this project to measure O_2/Ar from the underway systems on ships to constrain net community production. Stanley's lab at Wellesley also contains a convection oven for drying bottles, and a variety of other small lab equipment. Additionally, Wellesley College has a machine shop with welding capabilities, and limited free technical support available to all professors.

Computing: Stanley has access to multiple desktop and laptop computers which will be more than sufficient for calculating rates of production from the gas data obtained as part of the LTER. If required, she has access to workstations at Wellesley College.

Office: Stanley has an office near her laboratory.

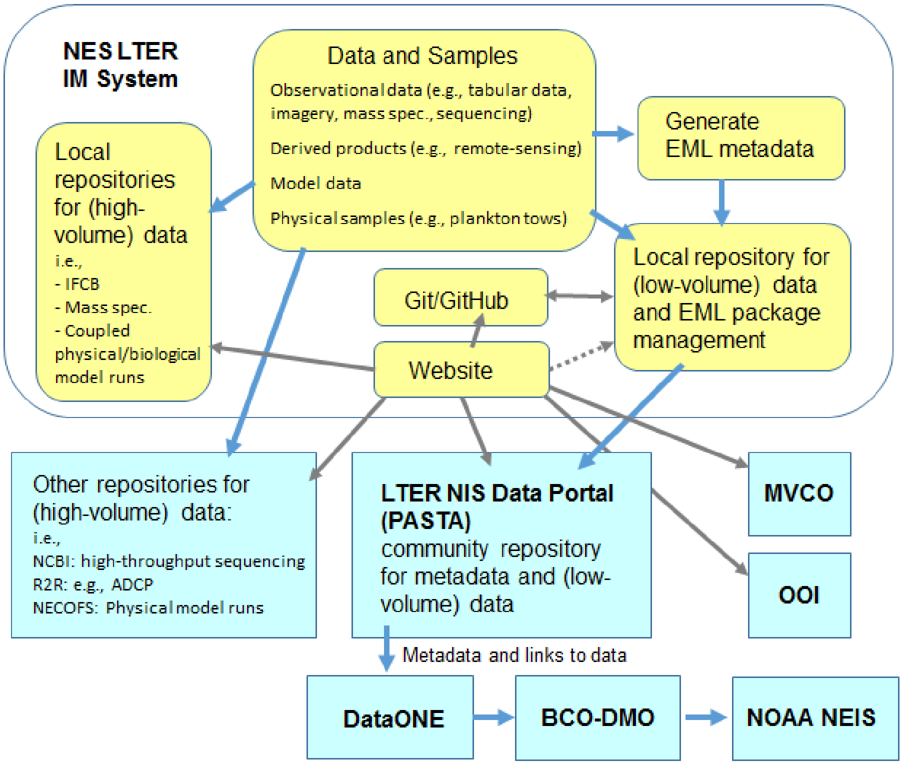
In-kind resources: The proposed work will be enabled through the generous student support offered by Wellesley College. Wellesley has a vibrant research program. Endowed funds and internal fellowships will support two summer students on this project each year. During the semester, students will do research on this project for credit and also one will be sponsored by the college's Sophomore Early Research Program in which work-study funds are given to low-income students who perform research in labs. Furthermore, Wellesley College in 2018 will be sponsoring its first STEM POSSEE, a program designed to bring to college a group of students, often from under-represented minorities or first generation college students. Wellesley College will be fully supporting these ten students, giving them an education at no cost to themselves and with no loans. One of these ten students will work on LTER research throughout her time at Wellesley. Thus she will be able to experience real research starting in her first year—a path that has been shown to dramatically increase retention of underrepresented minorities in STEM fields. Additionally, in 2018, the first year of the LTER program, Wellesley College will provide PI Stanley with a teaching release; in particular, the college will provide salary support for one semester without having her teach any classes.

DATA MANAGEMENT PLAN

1. Overview of Northeast U.S. Shelf (NES) LTER Data and Information Management (IM)

The primary goals of NES-LTER IM are to facilitate access to NES-LTER data by scientists, educators, and the public, and to curate those data with metadata to ensure discoverability and usability in the future. For core data sets, we will meet both of these goals by providing data packages inclusive of metadata directly to the LTER Network Information System (NIS). Core data sets will tend to be low-volume and/or low-frequency data that may be derived from high-volume and/or high-frequency raw data. Much of the high-volume and/or high-frequency raw data will also be accessible and discoverable through infrastructure maintained at other community repositories or at WHOI (see diagram).

The NES LTER IM team involves a communication network with an Information Manager, Stace Beaulieu, who will be involved in the entire data lifecycle from planning sample collection to contribution of core data sets and metadata to the LTER NIS. Beaulieu will participate in science planning meetings, coordinate data acquisition with the field research coordinator prior to and following cruises, and train co-PIs and their technicians, postdocs, and students in best practices for contributing data and metadata. To implement the provision of data packages to the LTER NIS and to administer local repositories, Beaulieu will work with WHOI Information Services as described in the Facilities Statement.



2. Types of data produced

2.1. Data. We will produce observational data, derived data products, and model data. Observational data will be obtained in near-real-time from moored underwater instruments, underway and from sampling on research cruises, and post-cruise with laboratory analyses. Observational data and derived products are categorized into the 5 LTER core areas in the Table 2 in the Project Description. A high-volume data example is high-throughput sequencing (HTS) data. A high-frequency data example is imagery from the moored Imaging FlowCytobot (IFCB). The derived core data sets for both these examples will be tabular records of categorized organisms.

2.2. Physical samples will include water samples, filters, plankton net samples, and fish specimens.

3. Data and metadata standards

3.1. Compliance with LTER NIS. Metadata will be provided to the LTER NIS in the Ecological Metadata Language (EML) standard (most recent version). Metadata will be generated by manual entry in a template or tool and may be automated for some data streams. Data provided to the LTER NIS will be in non-proprietary formats, e.g., comma separated values (CSV).

3.2. Compliance with Division of Ocean Sciences Sample and Data Policy. The Biological and Chemical Oceanography Data Management Office (BCO-DMO) will harvest NES-LTER metadata (which will include links to data) through DataONE. Underway data from University-National Oceanographic Laboratory System (UNOLS) cruises will be provided to the Rolling Deck to Repository (R2R). Some high-volume and/or high-frequency data will be provided to other community repositories, for which additional metadata and data standards apply [e.g., HTS data to National Center for Biotechnology Information (NCBI)]. Model data will utilize data and metadata formats familiar to the U.S. Integrated Ocean Observing System (IOOS) community (e.g., NetCDF format). Physical samples will be registered with the System for Earth Sample Registration (SESAR) to obtain International Geo Sample Number (IGSNs) for unique sample identification.

4. Policies for Access and Sharing

LTER-funded data will be made freely and publicly available following guidelines from the LTER Network Data Access Policy for Type I data. Type II data restrictions might apply to products from remote-sensing data if covered under prior licensing and to model data if used by commercial companies. Providers of data access are distinguished as the LTER NIS, other community repositories, or WHOI (see diagram). For example, data from the atmosphere-ocean model and the coupled physical-biological model will be available via THREDDS servers at the Northeast Coastal Ocean Forecast System (NECOFS) and at WHOI, respectively. Each repository may have its own user login for permissions to access during an embargo period not to exceed 2 years after collection. The NES-LTER website will provide links to these and other relevant repositories (dashed gray arrow indicates the possibility for the website to be integrated with a local database, e.g., by adopting a content management system utilized at existing LTER sites).

5. Policies for Re-use, Distribution

The primary policy for NES-LTER data re-use will be the LTER Network's General Data Use Agreement for Type I data. We will recommend citation with Digital Object Identifiers (DOIs) for data sets accessed through the LTER NIS Data Portal, and DOIs can be minted by the MBLWHOI Library for data sets accessed from local repositories. For those data provided to other community repositories, policies of those repositories apply.

6. Plans for Archiving and Preservation

We will facilitate the archiving of core data sets with the National Data Center for OCE-funded data, the NOAA Earth Information System (NEIS). For those data provided to other community repositories, archiving plans of those repositories apply. Local repositories at WHOI's data center will include backup and disaster recovery as described in the Facilities Statement. PIs will archive voucher and type specimens in their labs.

7. Expected milestones and deliverable products from data management

Year	Milestones	Deliverable products
1	Create project website; Adopt template or tool for generating EML metadata; Establish local repository for (low-volume) data and EML package management; Establish GitHub repository for processing scripts for core data sets	Initial EML packages provided to LTER NIS
2	Implement automated upload of EML core data packages to LTER NIS; Establish local repositories for high-volume data, e.g., mass spectrometry raw data; Ensure that our EML metadata can be harvested by BCO-DMO	Additional EML packages provided to LTER NIS; Metadata discoverable in BCO-DMO
3	Establish additional services as needed if more/different data are being acquired; Ensure pathways for ultimate archiving of data in NOAA NEIS	Additional EML packages provided to LTER NIS; Metadata and data harvested by NOAA NEIS

POSTDOCTORAL RESEARCHER MENTORING PLAN

This Postdoctoral Researcher (PR) Mentoring Plan establishes guidelines for work to be performed by PRs in support of research described in the project. We will train three PRs in this project, one PR to be hired by WHOI and two by URI. They will work on various phases of the project. Short-term and annual plans of work will be developed against which performance and progress will be measured. The annual plan of work will be shared among the project PIs and will be used as a basis for assessment and evaluation of progress and performance.

Specific tasks for the proposed effort will include plankton population dynamics / genetic diversity (for the PR working with Rynearson at URI); plankton rates, processes and transformations (for the PR working with Menden-Deuer at URI); coupled modeling development and implementation (for the PR working with Ji at WHOI); data production, analysis, and interpretation; preparation of presentations and publications; building and sustaining effective research collaborations; mapping out a career trajectory; and integrating personal and professional goals. Active engagement in the informal teaching and public outreach activities will be encouraged through participation in the Broader Impacts activities, as well as through invited lectures in courses at the participating institutions. The proposed project offers excellent opportunities for professional development and interdisciplinary research through close collaboration with the researchers, staff, and students at WHOI, URI, UMass and Wellesley College. The PRs will also have the opportunity to access all the PR training programs / courses in all institutions. They will be strongly encouraged to take full advantage of this opportunity to work with an accomplished and diverse team of researchers, educators, and outreach professionals.

In addition to the general mentoring program described above, WHOI has mentoring programs at both institutional and departmental levels. At the institutional level, WHOI hosts a Writing a Better Proposal workshop twice a year (winter and summer); regular meetings for postdocs with visiting federal agency program managers to discuss funding opportunities; 3 workshops per year for responsible conduct of research training; career development forums; a Postdoctoral Symposium every fall; and the annual Postdoctoral Breakfast Reception which convenes postdoctoral researchers, their institutional sponsors, and representatives from WHOI's leadership to discuss issues of potential importance to postdoctoral scientists, including the federal funding outlook. Incoming PRs are provided with the document Guidelines for Discussing Advisor-Postdoc Expectations and Responsibilities. The Biology Department at WHOI reviews PR progress every six months by a meeting of each PR with the Biology Department Postdoctoral Mentoring Committee (six scientists, untenured and tenured; Ji is one of the six committee members) to provide an objective assessment of progress and an expanded network of support for the postdoctoral researcher and sponsor. The mentoring committee is available to review job application materials such as cover letters and research / teaching statements for each postdoc. The PR from WHOI will be encouraged to access some of URI's mentoring programs (below).

The PRs from URI will be encouraged to participate in the WHOI mentoring program in addition to the URI-specific mentoring program that includes workshops on responsible conduct of research training, workshops on career development, programs designed to enhance scientific communication offered by the Metcalf Institute for Marine and Environmental Reporting and the Alan Alda Center for Communicating Science, workshops and one-on-one training in grant proposal preparation, targeted workshops and classes focused on publication and presentations. Because URI is an undergraduate teaching institution, PR sponsors will encourage PRs to participate in teaching and mentoring skills workshops and then work with undergraduates on a one-on-one basis in the lab, as well as practice and improve their teaching skills in the classroom.

All PRs will be encouraged to participate in the national LTER network and as permissible, contribute to synthesis workshops, participate in the *All Scientists* meeting and develop connections with other LTER scientists. This will lay a foundation for their career to integrate long-term ecological data, cross ecosystem and decipher decadal patterns.

PROJECT MANAGEMENT PLAN

1. Overview of Northeast U.S. Shelf (NES) LTER project management

Project management for the NES-LTER is inclusive of personnel, fiscal, administrative, institutional, and logistical components. The NES-LTER site will be based at the Woods Hole Oceanographic Institution (WHOI) with lead PI Sosik to oversee all aspects of project implementation and coordination. Three additional institutions are represented with co-PIs (University of Massachusetts, Dartmouth; University of Rhode Island; and Wellesley College). The total of 10 scientists involved as co-PIs will work as a team to plan, carry out, and integrate results from the various components of the proposed research. Co-PIs will effectively serve as the initial executive committee for the NES-LTER. Project management will involve a communication network (Fig. PMP 1) among an expanded team including other collaborators, an Information Manager, Education and Outreach Coordinator, technical staff, and students, with regular meetings and reporting on any changes in scope or timing with respect to a project baseline (Fig. PMP 2). As this project will initiate a new LTER site, the project schedule includes initial build phases followed by maintenance and growth phases for some of the sub-points in the project timeline. Involvement of students from diverse backgrounds and early-career researchers in project activities is encouraged (e.g., see Postdoctoral Mentoring Plan and Broader Impacts section of Project Description). Initial efforts will focus on the research activities of the co-PIs; efforts in later years of the project will include integrating other affiliated researchers (PIs with separately funded projects) into NES-LTER research activities.

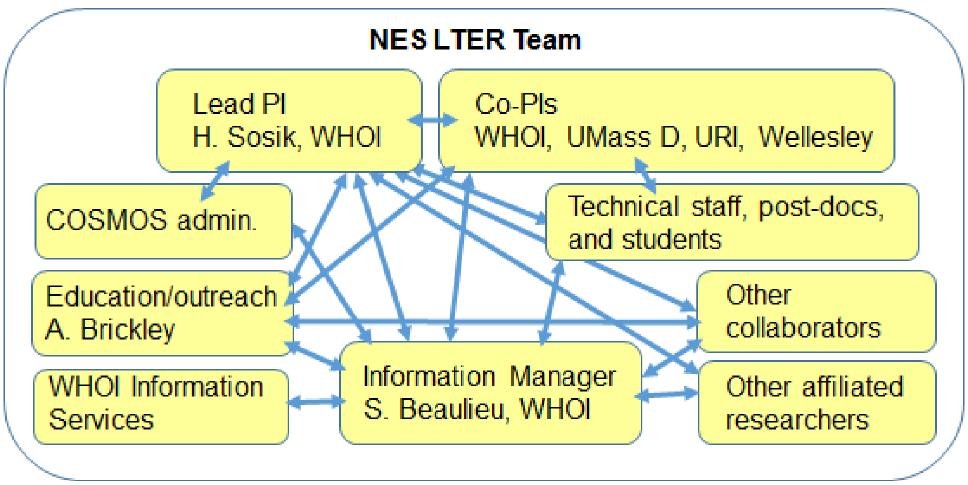


Fig. PMP 1. Communication network for the NES-LTER showing main points of contact.

2. Personnel roles in project management

The NES-LTER will be managed by lead PI Sosik, who will implement funding and research decisions in consultation with co-PIs. In leading the NES-LTER, Sosik brings extensive experience as Chief Scientist of the MVCO facility (since 2006), which includes responsibility for financial and operations team oversight, and in coordinating collaborative cross-disciplinary research teams (including technical projects in development of ocean observing instrumentation and cyberinfrastructure). Sosik will supervise the Information Manager, field research coordinator, and Center for Ocean, Seafloor and Marine Observing Systems (COSMOS) administrative professional(s) (as described below), as well as project personnel conducting sampling on NOAA-supported regional survey cruises and LTER-supported cross-shelf transect cruises. Sosik will also be the point-of-contact with OOI, other collaborators identified in Letters of Collaboration (see Supplemental Documentation), and other affiliated researchers who would like to initiate new research in association with the NES-LTER.

Co-PIs will participate in regular meetings and, along with Sosik, will effectively serve as the initial executive committee for the NES-LTER. These 10 scientists presently represent major research emphases of the NES-LTER: Beaulieu (Information Management and Education/Outreach), Chen (physical modeling), Ji (coupled biological-physical modeling and numerical ecosystem simulations), Lentz (physical oceanography and disturbance patterns), Llopiz (for trophic dynamics, zooplankton, and fish ecology), Menden-Deuer (protist ecology, plankton dynamics and rate processes), Neubert (theoretical and mathematical ecology), Rynearson (molecular diversity characterization across major domains of life), Sosik (plankton community composition and phytoplankton ecology), Stanley (gas tracer biogeochemistry, rate process, and productivity).

The NES-LTER will employ a half-time Information Manager at WHOI, Stace Beaulieu (also a co-PI and marine biodiversity expert), who will be point-of-contact for sharing data and metadata (see Data Management Plan). Beaulieu will work with WHOI Information Services (see Facilities statement). Beaulieu will also assist with project coordination by providing regular reports on deliverables and changes in schedule with respect to the project baseline. Beaulieu also will coordinate with the LTER national office for Network Databases.

The NES-LTER will employ a quarter time Education and Outreach Coordinator, Annette Brickley, to be supervised by co-PI Beaulieu. Brickley will coordinate the LTER Schoolyard program, inclusive of Research Experiences for Teachers. One of the supported technical staff at WHOI, E. Crockford, will serve as field research coordinator, including point-of-contact for cruise preparation. COSMOS administrative professional(s) will assist with communications, requests for payments, and travel coordination, among other administrative duties. Individual PIs and staff responsible for components of the proposed research and broader impacts are also listed in the detailed version of our project baseline (Fig. PMP 2). Ship and observatory-based field work will be conducted with support from an experienced team of technical professionals (7 at WHOI and 2 at URI).

We anticipate engaging at least 2 postdoctoral researchers, 2 graduate students, and 7 undergraduate students per year in the observations, modeling, and synthesis, with these numbers growing as the NES-LTER matures and research affiliates join. LTER-supported REU students will be coordinated through well-supported existing programs: the Woods Hole Partnership Education Program (PEP) (see Letter from Ambrose Jearld), WHOI's Summer Student Fellow program, Wellelsey's Sophomore Early Research and STEM POSSE programs, and URI's Summer Undergraduate Research Fellowship in Oceanography.

Other collaborators or contributors are those unfunded individuals who provided Letters of Collaboration (see Supplemental Documentation), including collaborators from NOAA's Northeast Fisheries Science Center and Geophysical Fluid Dynamics Laboratory, operators of NSF's Ocean Observatories Initiative Pioneer Array, and education specialists.

3. Fiscal, administrative, and institutional components

The NES-LTER site will be based at WHOI with lead PI Sosik who will oversee the project budget, administration, and representation in the national LTER Science Council. Sosik will implement funding and research decisions in consultation with co-PIs. The funds within NES-LTER are distributed according to needs for each sub-point in the project timeline, rather than proportionally to individual PIs. As this project will initiate a new LTER site, initial spending (in year 1) is focused towards permanent equipment. Each WHOI co-PI will be responsible for monitoring his/her respective budget sub-point. Three additional institutions with subawards are represented with co-PIs from UMass Dartmouth, University of Rhode Island, and Wellesley College. Each co-PI with a subaward will be responsible for monitoring his/her respective budget with regular reporting to WHOI and invoice approvals by Sosik. Sosik will be assisted in providing these support activities by an Administrative Professional provided through the COSMOS office at WHOI (see Facilities statement).

4. Communication plan

Internal communication among the NES-LTER participants will include monthly video-conferences. Monthly meetings will be open to all participants and cover business (e.g., site administration, proposed research projects, cruise planning, data management, education activities) and may include an invited presentation and/or discussion, e.g., a student practice talk. Notes of monthly meetings will be posted on the NES-LTER website. Each year a full-day, annual meeting will be scheduled while preparing the

Annual Report, and we will encourage participation in person. Day-to-day communications will be facilitated by an email listserv. Additional communications will include unfunded collaborators, including those who have contributed Letters of Collaboration for this proposal (see Supplemental Documentation), as well as others who join as the project matures. For external communication within the LTER network, we anticipate that the new LTER Network Communications Office (NCO) will implement an email listserv and/or newsletter, to which we will contribute. The Information Manager will attend the annual LTER Information Managers Meeting. At least 2 participants from the NES-LTER will attend the LTER All Scientists Meeting.

5. Logistical components and project baseline

As this project will initiate a new LTER site, the project schedule includes initial purchasing or build phases followed by maintenance and growth phases for some of the sub-points in the project timeline.

Our project baseline was set using free, online interactive software (gantter.com) that will facilitate easy access and updating throughout the project lifetime.

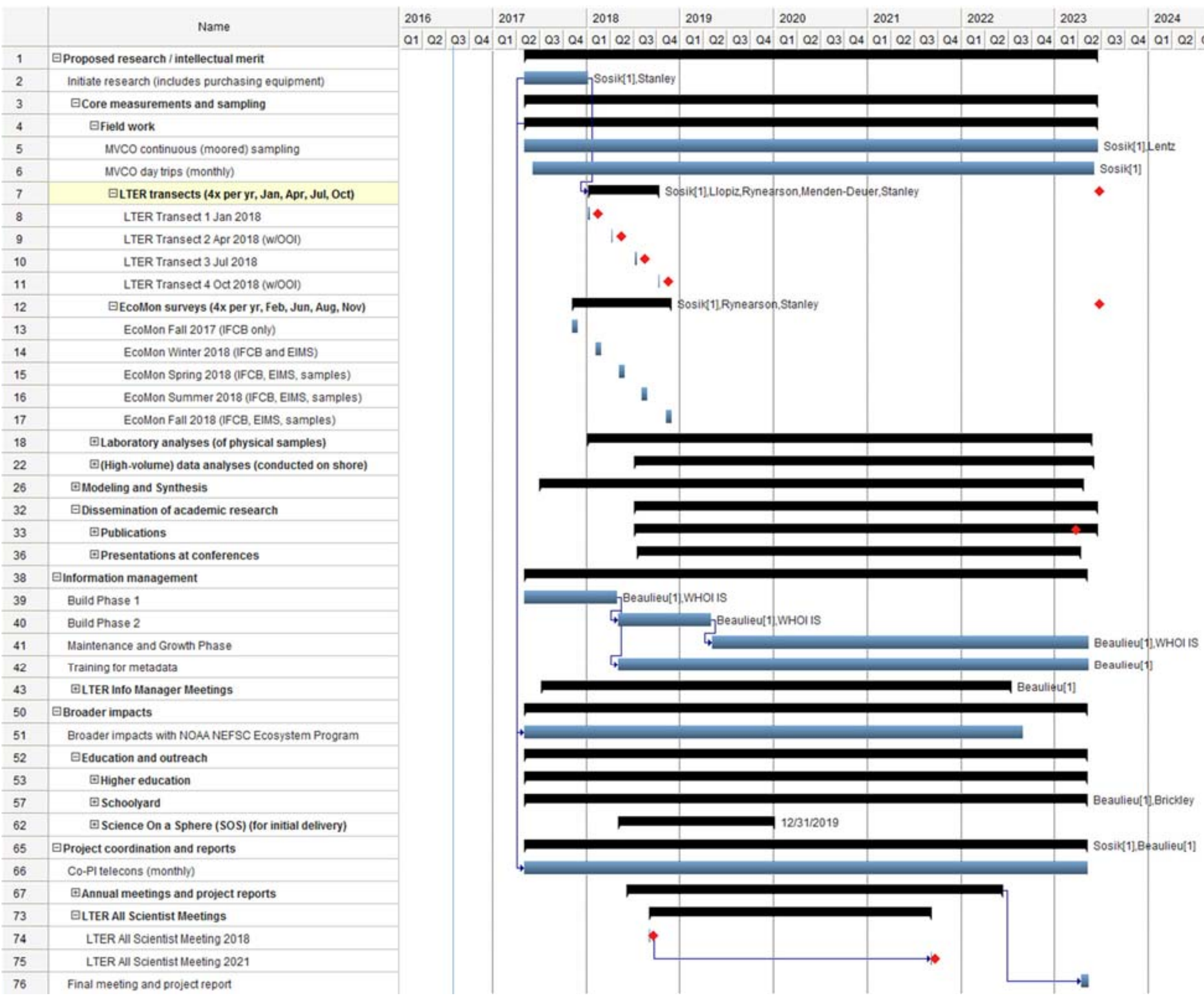


Fig. PMP 2. Gantt chart for implementation of NES LTER. In the full interactive interface (shared with all team members), sub-points in the project timeline can be expanded to show individual PI responsibilities (e.g., laboratory analyses of physical samples) and to show discrete events, such as individual cruises. Multiple levels of organization allow many details to be encapsulated succinctly, and will assist with planning, oversight, and reporting. For clarity in this static view, only some detail of first year of cruises and selected Broader Impacts and data management activities has been expanded.