2014 FATE PROPOSAL
Development of Zooplankton Community Indices for the Northeast Continental Shelf LME

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Background
Zooplankton perform critical ecosystem functions by transferring energy between trophic levels and providing key forage for resource species. Indeed, over a global scale, the amount of primary productivity that is channeled to mesozooplankton is more highly correlated with fishery yields than primary productivity itself (Friedland et al. 2012). Long-term changes in zooplankton biomass and species composition have also been linked to large shifts in the biomass and recruitment success of upper trophic levels in a variety of marine regions (McGowan et al., 1998, Beaugrand et al., 2003, Alheit and Niquen, 2004, Beaugrand and Reid, 2003, Mackas et al., 2007, Hipfner, 2008, Bi et al., 2011, Hunt et al., 2011, Tansichuk and Routledge, 2011, Friedland et al. 2013). In the California Current Large Marine Ecosystem (LME) and the Northeast Atlantic Ocean, zooplankton have proven to be effective ecosystem indicators of fisheries productivity (Beaugrand et al. 2003, Peterson 2009, Burke et al. 2012).

It has been suggested that changes in zooplankton productivity may also be one of the most important pathways for climate to impact fish resources in the Mid-Atlantic Bight (Mountain 2002). In the Gulf of Maine and Georges Bank regions, the linkage between climate, zooplankton, and cod and haddock recruitment success has been more explicitly described as a function of zooplankton community structure and species specific abundances (Mountain and Kane 2009, Friedland et al. 2013). However, even if the potential of zooplankton as a fishery-relevant ecosystem indicator is clear, zooplankton indices have been limited to biomass indices and community indices for a segment of the ecosystem and for only a few fish species. No zooplankton indices have been developed for the entire Northeast Continental Shelf LME (NES LME) and all of its constituents Ecological Production Regions (EPR).

An assessment of zooplankton variability and its drivers at a fishery-relevant scale is essential to the development of such ecosystem indicators. Variability in zooplankton dynamics and community structure in the NES LME have been studied in the past and documented decadal scale shifts in zooplankton abundance (Pershing et al. 2005, Kane 2007, Kane and Prezioso 2008, Kane 2009, Pershing et al. 2010). These shifts have been associated with size specific responses of large bodied zooplankton taxa such as Calanus finmarchicus, which declined in abundance from the early 1990s to the early 2000s, while smaller species such as Oithona spp. and Centropages typicus increased in abundance (Pershing et al. 2005, Kane 2007, Pershing et al. 2010). While these studies were vital in demonstrating historical changes in zooplankton community composition, most were specific to particular NES LME regions such as Georges Bank and the Gulf of Maine (Kane 2007, 2009, Pershing 2005). The only two large scale zooplankton studies in the NES LME focused solely on one species (Kane and Prezioso 2008) or on annual abundance anomalies (Pershing et al. 2010), rather than assessing historical variability in zooplankton dynamics during specific seasonal windows.
However, a seasonal scale characterization of these data will more likely provide data relevant to fish species since most species have spawning and juvenile migration windows which are narrowly defined in time and space. For example, recent declines in winter-spawning cod in the NE Continental Shelf have been associated with a reduced abundance of the copepod *Pseudocalanus* spp. in spring, while the decrease in the copepod *Centropages typicus* in autumn has affected spring spawning cod (Friedland et al. 2013). If we had examined zooplankton abundance annually as has been done in the past, we would not have detected the change in seasonal abundances and its potential effect on cod. Similarly, in the Northeast Pacific, the presence of lipid rich northern copepods, such as *Calanus marshallae* and *Pseudocalanus* spp., during the salmon juvenile migration in spring and early summer has been linked to increased salmon survival (Peterson and Schwing 2003, Bi et al. 2011, Burke et al. 2012). Clearly, a coast-wide, seasonal assessment of the temporal and spatial variability in zooplankton community composition is required to further our mechanistic understanding of the observed shifts in fish assemblages and distribution in the region (Nye et al. 2009, Lucey and Nye 2010) and to inform ecosystem assessment initiatives.

A seasonal scale characterization of zooplankton anomalies is also necessary to investigate potential drivers of the observed changes in zooplankton community composition (Pershing et al. 2010). Reasons for the observed shift in zooplankton assemblages have been attributed both to top-down and bottom-up processes (Frank et al. 2005, Pershing et al. 2005). Frank et al. (2005) proposed that the demise of Atlantic cod on the Canadian Shelf produced a trophic cascade that led to an increase in planktivorous forage fish species, phytoplankton, and small copepods, and to a reduction in *C. finmarchicus* biomass. However, in the late 2000s, even under persistent high densities of forage fish, *C. finmarchus* biomass was again on an increasing trend, leading Head and Sameoto (2007) to conclude that mechanisms for the observed zooplankton community shift may be more complex than the trophic cascade hypothesis. Key to this newfound understanding was the observation of a seasonal component to the observed annual changes. The increase in phytoplankton and small copepod biomass was limited to the winter period, while that of *C. finmarchicus* to the summer season (Head and Sameoto 2007). It has been hypothesized that the increase in small copepods was a bottom-up response to increased winter chlorophyll biomass following increased winter stratification (Head and Sameoto 2007, Pershing et al. 2005). A variety of potential causes, including changes in advective inputs and shifts in spring bloom magnitude, have also been proposed to explain the shift in zooplankton community composition (Head and Sameoto 2007, Pershing et al. 2010, Pershing et al. 2005). However, hypothesized associations between environmental parameters and zooplankton community composition have yet to be examined quantitatively, reducing our ability to predict future impacts of climate change on fish productivity.

Species are likely to shift their seasonal cycle under climate change (Parmesan 2006), and zooplankton time series from other temperate regions have shown large (1-3 months) changes in seasonal timing in association with temperature variability (Mackas et al. 2012). Since fish larval survival in temperate systems may in part depend on the synchronization with the seasonal pulse of its zooplankton prey (Hjort 1914, Cushing 1975), there may be potential for a decoupling of the trophic interactions sustaining the NE continental shelf food web under future climate change. Yet, characterization of coast-wide and ecoregion specific, long-term changes in zooplankton community composition at seasonal scales and of its drivers remain a critical data requirement for the NES LME, diminishing our ability to assess how prey fields of important fish species may shift under changing environmental conditions.

**Approach**
Here we propose to develop a comprehensive, coast-wide suite of zooplankton community indices for the NES LME. The specific objectives for the project are as follows:

1) Develop zooplankton based ecosystem indicators for the NE Continental Shelf LME and its constituent Ecological Production Units that serve as the spatial framework for the Integrated Ecosystem Assessment (IEA) focusing on ecologically relevant seasons.

2) Build empirical relationships linking zooplankton abundance and community structure to hydrographic, physical, and environmental variables.

Data sources
This work will make use of the existing Ecosystem Monitoring Program (ECOMON) zooplankton data series from the National Marine Fisheries Service, Northeast Fisheries Science Center. We will examine how zooplankton community composition has changed spatially and inter-annually over the past 37 years using seasonal groupings that can be resolved in the data series. The analysis will not be restricted to copepods, and will encompass the entire mesozooplankton community.

Long-term data series of hydrographic, physical, and environmental variables such as temperature at depth, salinity and stratification will be obtained from CTD casts collected during the zooplankton surveys as well as monthly, gridded (1°x1° boxes), surface marine data from the International Comprehensive Ocean-Atmosphere Data Set (ICOADS) from 1960-present. Large-scale climate indices will be obtained from the NOAA Climate Prediction Center website.

Data Analysis
Zooplankton Indices:
Zooplankton are indicators of both trophic structure and physical ocean conditions (Peterson 2009). As such, timeseries of both copepod species richness and northern copepod biomass anomalies have been used as ecosystem indicators in the Northern California Current (Peterson and Schwing 2003, Hoff and Peterson 2006, Peterson 2009). As no coast-wide analysis of zooplankton variability has been conducted in the NES LME at ecologically relevant seasonal scales, the first step in building zooplankton indices for this region will assess the long-term spatial and temporal variability in zooplankton abundance and community structure by season through the use of multivariate statistical methods, such as hierarchical cluster analysis, and non-metric multidimensional scaling (MDS) ordinations. Modes of zooplankton community variability will be identified from the MDS analysis and indicator zooplankton species of each mode will be determined using the indicator value method (Dufrene and Legendre 1997). The zooplankton community structure modes, described by the MDS ordination scores, and anomalies in their respective indicator species will serve as one set of zooplankton indicators. This analysis will be conducted for each of the four Ecological Production Units (EPU) in the NES LME (Fig.1). In addition, we will construct zooplankton indices specific to

Figure 1: Map of NES LME broken down by Ecological Production Units (EPU)
single fish species in the NES LME by extracting from the zooplankton data set anomalies in those zooplankton taxa that have been identified in the literature and by an ongoing larval fish diet analysis study of J. Nye and collaborators (funded by another source) as prey of each specific fish species during their juvenile phase.

For many fishery resources such as salmon, the energy storage and critical size reached after their first summer at sea is an important proxy of future survival (Pearcy 1992, Beamish and Mahnken 2001). Thus, low availability of energy rich prey in the juvenile phase may impair survival potential to later stages. Therefore, we will also develop an energy-based zooplankton index. Zooplankton species will be characterized by their biomass (g wet mass) and energy density values (kJ/g wet mass) collated from the literature to determine their nutritional value (kJ) following Foy and Norcross (1999). The spatial and temporal variability in the energy based zooplankton index (sum of kJ across species) will be assessed for each EPU and by season. As per the abundance based analysis, an energy-based index specific to each fishery resource will also be constructed.

Finally, to assess the potential of these indices to inform research on the growth and recruitment of resource species, we will compare temporal and spatial shifts in zooplankton community structure to observed shifts in fish assemblages (Lucey and Nye 2009). Also, recruitment time series expressed as anomalies of the major resource species in the NES LME will be related to the zooplankton indices to determine which zooplankton indices may be incorporated into stock specific models to improve their forecasting capabilities.

We plan on delivering routines that compute zooplankton community indices (developed in R language) that can be put into an operational framework supporting an Integrated Ecosystem Assessment of the NES LME as well as single species assessments. These routines will also produce visualizations of the indices (e.g. Fig. 2) that could be accessed online by a variety of stakeholders and that would be easily updated following each ECOMON survey.

Environmental Forcing of Zooplankton Dynamics

We will develop empirical relationships between zooplankton indices (indicator species anomalies, zooplankton community modes, and abundance and energy based stock specific indices) and environmental forcing using the appropriate linear or non-linear models. A suite of local and large-scale environmental variables such as sea surface temperature, bottom temperature, surface salinity, bottom salinity, the Atlantic Multidecadal Oscillation Index (AMO), the North Atlantic Oscillation (NAO) Index, and the Gulf Stream North Wall Index (GSI) will be considered. We will examine these indices at a variety of temporal lags relevant to zooplankton dynamics.

Benefits

This project will contribute to the FATE goal of developing leading ecological indicators to be used in marine ecosystem assessments. Indeed, scoping and indicator development are two of the most important, but difficult processes in developing an IEA (Levin et al. 2009). The zooplankton indices resulting from this project will be readily incorporated into Integrated Ecosystem Assessments of the NES LME region. We also see the potential of these indices to inform research on...
the growth and recruitment of resource species. For example, the same indices could be readily integrated into stock-recruitment relationships of fishery resources in the region. Furthermore, the development of empirical relationships between the biologically relevant zooplankton indices and environmental variables will further our understanding of the functional relationship between environmental forcing and variability in fish species. It will also allow for the development of future projections of the zooplankton indices to inform resource managers on the status of the prey fields of fish species in the future and improve capabilities for effective management of marine resources under a changing climate. An evaluation of trends in zooplankton functional groups might inform and help parameterize ecosystem models such as Atlantis that can be used in future Management Strategy Evaluation in a Ecosystem based fisheries management context.

The indices will be operational and easily accessed online by resource managers as data files and visualizations. Routines to compute the indices will be developed in the R language to allow for the indices to be easily updated following each bimonthly ECOMON survey from the National Marine Fisheries Service, Northeast Science Center. The project will support the collaboration of fishery scientists, oceanographers, and climate scientists at NOAA Fishery Laboratories and other institutions with the goal of improving ecosystem-based fishery management in the region.

**Deliverables**

- Operational zooplankton indices and a routine to easily update the zooplankton indices time series as newly collected data becomes available.
- Visualizations of the indices and the indices themselves will be made available online through the National Marine Fisheries Service, Northeast Science Center website.
- At least two peer-reviewed publications.
- Presentations at the annual FATE meetings in 2014 and 2015 and at least one international meeting such as ICES, PICES or Ocean Sciences.

**Timeline**

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<tr>
<td>Assembly and pre-processing of zooplankton and physical data</td>
<td>Development of zooplankton indices</td>
<td>Development of models relating environmental variables to zooplankton indices</td>
<td>Submit manuscripts</td>
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<td>Collation of zooplankton energy density values from the literature</td>
<td>Presentation of preliminary findings at FATE Annual Meeting</td>
<td>Finalization of the open source R-code to compute the indices and produce coast-wide visualizations of them</td>
<td>Present final results at FATE Annual Meeting</td>
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<td>Multivariate statistical analysis of zooplankton data</td>
<td>Comparison of zooplankton indices to shifts in fish assemblages and species specific recruitment</td>
<td>Contribute to the NES Ecosystem Status Report (ESR) and IEA</td>
<td>Present final results at an international conference</td>
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<td>Collation of fish prey preferences from the literature and ongoing larval fish diet analysis funded by another source</td>
<td>Include zooplankton indices in Ecosystem Advisory</td>
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References
Burke BJ, Peterson WT, Beckman BR, Morgan C, Daly EA, Litz M. 2012. Multivariate models of adult Pacific salmon returns. PLOS one 8: e54134.


