Proposal for NOAA Fisheries And The Environment FY 2015

Is Atlantic cod and haddock recruitment influenced by the planktonic environment and feeding success during the larval stage?

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FATE Research Priorities: 1, 2, 4

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Budget breakdown
- Year 1, Northeast Fisheries Science Center: $2,334
- Year 1, Woods Hole Oceanographic Institution: $53,389
- Year 2, Northeast Fisheries Science Center: $4,118
- Year 2, Woods Hole Oceanographic Institution: $56,180

BACKGROUND

Atlantic cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) have long been the foundation of the New England groundfish fishery. Both species are divided into Georges Bank (GB) and Gulf of Maine (GOM) stocks. These four stocks share a history of overexploitation that peaked in the early 1990s and resulted in low population levels. However, since that time the trajectories of the four stocks have diverged. Georges Bank haddock has been fully recovered for about a decade due to many strong year classes and reduced fishing mortality. The GOM haddock stock briefly recovered in the early 2000s, due to a strong 1998 year class, declined again until 2010, but is now rebuilt based on another set of strong year classes. In contrast to haddock, both GB cod and GOM cod have remained at low levels. Most notably, the GOM cod stock remained at relatively steady but low levels from 1990 through 2009, before declining an additional 80% through 2013. This decline is attributed to a failure to control fishing mortality and a string of 5-6 consecutive years of poor recruitment.

Various explanations have been proposed to explain the recruitment patterns of these stocks individually, including larval transport (Churchill et al. 2010), maternal condition (Friedland et al. 2008; Leaf and Friedland 2014), ocean warming (Fogarty et al. 2008), and larval prey availability (Friedland et al. 2013). The decadal scale contrast in recruitment between Georges Bank cod and haddock has also been linked to changes in the zooplankton community (Mountain and Kane 2010). However, most of these analyses are based on correlations of recruitment from the stock assessments to regional-scale indices, with the additional predictions of the proposed mechanisms rarely tested using additional laboratory or field data. Additionally, only one of these studies has been presented at a stock assessment (Churchill 2010); this environment-recruitment correlation failed upon reexamination (NEFSC 2012a).

The comparative approach to examining the recruitment patterns in these four stocks holds substantial promise due to similarities in spawning and early life history strategies, including: 1) partial but not complete overlap in spawning location and timing for the two species, 2) similarities in egg sizes, hatch sizes, and general larval morphology, and 3) seemingly similar larval diets between the two species. Additionally, the recruitment time series of these four stocks appear neither completely independent nor completely synchronous on an inter-annual basis (e.g. some, but not all, strong year classes are shared by the two haddock stocks; some concurrent cod and haddock recruitment events occur within regions) (Fogarty et al. 2001).

There are a number of reasons to hypothesize that inter-annual variability in larval environment, and in particular larval feeding, is driving recruitment in these stocks. For GB haddock, strong year classes are generally evident by the end of the summer (i.e. the August scallop survey) following spring spawning. Additionally, for year classes shared between GB and GOM haddock, new recruits occur at two upstream locations that are not linked by plausible transport pathways. This distribution of recruits suggests that recruitment is being driven by a shared environmental driver rather than dispersal from a common spawning location. The transport processes on GB and in the GOM are also notably different; transport alone would not be expected to drive synchrony in recruitment in these two stocks. Zooplankton assemblages and temperature are correlated among regions, but not perfectly so, and may thus explain why some year classes are shared among stocks and some are not.

The long history of fisheries research in New England, together with a few often-cited papers on the feeding dynamics of cod and haddock larvae from GB (Kane, 1984; Lough et al., 1996; Lough and Mountain, 1996), give the impression that we already know enough about larval trophodynamics for these species (Heath and Lough, 2007). While a remarkable number of

larvae from these studies has been inspected for diet analyses (over 17,000 individuals examined by Lough and Mountain (1996)—but from only 2 stations in 2 years), the spatial and temporal coverage is severely lacking, and results are unable to be placed in a recruitment-relevant context or be related to prevailing environmental conditions in the regions over multiple years. A recent report has expanded our knowledge of cod and haddock feeding on GB to 5 years in the 1990s (Broughton and Lough, 2010), but, again, despite a sample size of ~3500 inspected larvae, spatial coverage was limited (2 stations each year), and temporal variability in feeding success and diets was not evident, likely due to similar environmental conditions during the 5 years.

The most remarkable gap in our knowledge is the nearly complete lack of information on larval cod and haddock feeding in the GOM. Only one study has examined the diets of cod and haddock from the GOM (Marak, 1960) and it had a low samples size (~50 individuals <18 mm) and no breakdown by species (i.e. haddock vs. cod) or location (i.e. GB vs. GOM). Thus, in addition to a need for basic knowledge of processes governing larval survival of cod and haddock in the GOM, there is a complete dearth of information about any possible role of a changing ecosystem—including zooplankton abundance and species composition—in determining recruitment success in these important fishery species. We propose to substantially add to our understanding of the environmental influences on cod and haddock larval survival by taking a temporally and spatially broad-scale, comparative approach that examines feeding success and zooplankton conditions during contrasting regimes and levels of recruitment success.

APPROACH

We propose to evaluate whether variability in the larval environment, prey selection and feeding success can explain the contrasting recruitment patterns of the GOM and GB stocks of Atlantic cod and haddock. We will evaluate concurrently collected larval and zooplankton data, and we will develop a new dataset on larval feeding from archived ichthyoplankton samples. The research team is cross-disciplinary and includes the lead assessment scientist for GOM Atlantic cod and GOM haddock (Palmer), a NEFSC oceanographer (Richardson), and a WHOI researcher with expertise in larval fish feeding dynamics (Llopiz).

Specific objectives

1. *The environmental conditions experienced by fish early life stages can be decoupled from larger regional-scale patterns due to variability in spawning time or location and fine-scale larval distributions. Thus, we will examine inter-annual differences among stocks in the zooplankton communities and temperature environment experienced by the larvae using concurrently collected oceanographic, zooplankton and ichthyoplankton data.*
2. *We will examine inter-annual, regional, and species-specific differences in both feeding success and diet composition of larval cod and haddock from Georges Bank and the Gulf of Maine, and will relate larval feeding success and diets to physical and biological conditions, including ambient zooplankton abundance and species composition.*
3. *We will test the hypothesis that the contrasting patterns in recruitment success among the four stocks can be linked to larval feeding success and environmental drivers. If the previous analyses support it, we will then integrate a zooplankton index into the assessment models stock recruitment function.*

***Available data and samples*—**The Northeast Fisheries Science Center has been collecting zooplankton and ichthyoplankton samples since 1977 on approximately 6 shelfwide surveys per year. Samples have been collected using a 60 cm-333 μm bongo net with one side preserved for

zooplankton analysis and the other for ichthyoplankton analysis. Temperature and salinity were measured at all stations. For zooplankton analysis, an aliquot of approximately 500 organisms are removed for identification and enumeration (Kane 2007). All ichthyoplankton are identified, counted, and up to 50 individuals of each species are measured (Richardson et al. 2010). Identified ichthyoplankton dating back to 1982 are archived at the Narragansett Laboratory; 15,000-25,000 individuals at 2000-3000 stations are available for each cod and haddock.

***Stability of spawning strategy*—**We will evaluate spatial shifts in the larval distribution and temporal shifts in the seasonality of egg hatching for the two stocks of haddock and cod. The motivation for this analysis is that changes in spawning timing/location may dampen or magnify external environmental variability experienced by a stock. Approaches to evaluating shifts in spawning seasonality have been developed as a part of a previous FATE project (Hare et al. FY11) and have been presented at the Atlantic herring stock assessment. Briefly, spawning seasonality is estimated within a larval index model, based on the abundance and age distribution of larvae sampled on multiple surveys (Richardson et al. 2010). This technique is well suited for cod and haddock, which are typically sampled on three cruises per year (Jan/Feb, Mar/Apr, May). For GOM cod we will modify this approach to address the bi-modality in spawning. We will evaluate spatial shifts in spawning distribution by calculating the center of biomass of newly hatched larvae for each year, for each stock, using an approach that accounts for the stratified random sampling design of the surveys (see Richardson et al. 2014). Finally, we will calculate the stratified mean temperature experienced by larvae (i.e. station temperature weighted by larval abundance, strata area, and number of tows per strata) for each stock based on the ichthyoplankton sampling on the spring trawl survey. The timing of this survey has remained reasonably consistent over recent decades, and typically has the highest larval abundances. The overall intent of these analyses is to evaluate whether the established temperature indices for the region (e.g. EcoAp 2009) are actually reflective of the environment experienced by larvae and thus should be considered in further analyses as a direct driver of recruitment variability.

***Zooplankton community analysis*—**Previous multivariate analyses of the NEFSC zooplankton data have highlighted decadal scale patterns in the zooplankton communities on the northeast U.S. continental shelf (Pershing et al. 2005, Kane 2007, Hare and Kane 2012; Fig. 1). These patterns, which encompass the full annual cycle of sampled zooplankton data, have been correlated with cod and haddock recruitment success (Pershing et al. 2005, Mountain and Kane 2010). However, much of the interdecadal variability can be attributed to a change in fall/early-winter zooplankton dynamics when cod and haddock larvae are not typically present; these prominent changes have been attributed to large scale changes in salinity and the fall phytoplankton bloom (Durbin et al 2003; Greene and Pershing 2007).

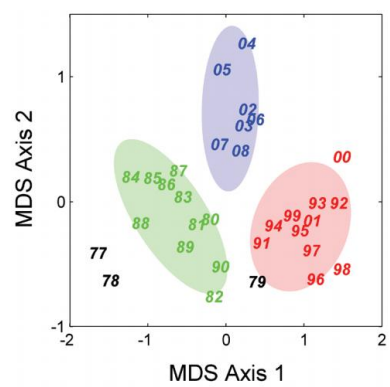

Figure 1. Multi-dimensional scaling ordination of the annual zooplankton anomalies on Georges Bank (Kane 2007 updated in Hare and Kane 2012).

We will seek to address 1) the extent to which the zooplankton communities actually experienced by cod and haddock larvae on GB and in the GOM reflect these larger-scale changes, and 2) the extent to which larvae from the four stocks experience similar zooplankton communities. Kane (2007) used hierarchical agglomerative clustering analysis and non-metric

multi-dimensional scaling (MDS) on annual zooplankton abundance anomalies to resolve groupings of similar years (Fig. 1). We will modify this approach using larval abundance data for each stock to weight the station level zooplankton data that is used to generate the input matrix for this analysis. The resulting input matrix will thus contain a year for each stock (e.g. 2003 GOM cod) as well as an annual anomaly for each zooplankton taxon based only on the stations where cod or haddock larvae were sampled. This approach will thus only capture interannual variability in the zooplankton community at the locations and times that the larvae of a stock occur. The ordination will allow us to evaluate whether interannual, regional, or species-specific differences in zooplankton community are most prominent. We predict that in years when the GB and GOM stocks of a species experience synchronous recruitment events (e.g. 1998 haddock) the zooplankton community will be similar between stocks, while in years when only one stock recruits well, the ordination will show a difference in zooplankton communities.

***Diet analysis*—**The scale of available samples and the effort required will preclude generating a full time series of larval feeding success and diet for each stock. Rather we will use the recruitment time series and the zooplankton analysis described above to guide our diet analysis. The intent will be to choose years that have contrasting recruitment patterns and zooplankton communities. We will aim to inspect at least 2000 daytime-collected larvae (1000 per species) to obtain data on feeding success (as measured by feeding incidence and prey biomass per larva) and diet composition over broad ontogenetic, spatial, seasonal, and annual scales.

From each station to be examined, up to 10 larvae per species will be randomly selected without regard to size since the goal is to obtain population-relevant results on feeding success and prey consumption. This modest number of individuals per station will minimize the likely redundancy of within-station feeding data and maximize the spatial and temporal coverage of the study. Individual larvae will be measured for notochord or standard length and dissected with a microscalpel and minutien pins to remove the entire alimentary canal. Excised prey will be enumerated, measured for length, and identified to the lowest taxonomic level practical (Llopiz and Cowen 2008, Llopiz et al. 2010).

***Development of stock specific zooplankton indices*—**Strong year classes in marine fishes have been hypothesized to occur when adequate amounts of prey overlap with larvae. The integrated annual prey abundance, the timing of occurrence, and the spatial patterns of occurrence all influence whether adequate prey is available; metrics that capture only one of these processes are not optimal for testing recruitment variability. With paired ichthyoplankton/zooplankton samples and information on larval prey preferences, it is possible to estimate the average prey availability at the locations larvae occur. As with the zooplankton community analysis we will calculate a zooplankton index that is weighted by larval abundance and accounts for the random stratified sampling design. The zooplankton taxa chosen for this index will be based on the larval diet data. One acknowledged limitation of our analyses will be our ability to describe temporal and spatial patterns in copepod nauplii abundance (due to the 333-µm mesh size). Measuring of the prey extracted from larvae will help us know what taxa might not be accurately represented in the zooplankton samples, and feeding intensity on small prey (e.g. nauplii) by the larvae can still be used as a proxy for availability. A subset of 150-um mesh samples (paired with the standard net) that are available from 2001-present will also help elucidate prey extrusion patterns (though likely not for nauplii).

***Evaluation of the index within the assessment model*—**Recent additions and modifications to the Age-Structured Assessment Model (ASAP) have allowed for the evaluation of environmental drivers of recruitment directly in the stock assessment model (NEFSC 2012b). We will use these models to evaluate the zooplankton index we develop and the regional temperature index if deemed appropriate. Ultimately, one of the benefits of developing a mechanistic understanding of recruitment variability is that it may allow for the development of rebuilding targets and harvest strategies that account for long-term changes in productivity (Collie et al. 2012, Bell et al. 2014). Ongoing work is evaluating the use of state-space models in projections. These models assume that the environmental driver of recruitment cannot be forecast, but that it is autocorrelated rather than completely random. Our proposed work is focused on understanding the mechanisms underlying recruitment variability rather than on development of new assessment models. However, if a successful predictor of recruitment is found, our work is designed to fit well into the ongoing assessment modeling efforts (funded and proposed by others through other RFPs).

BENEFITS

The review panel for the GOM cod assessment update in the summer of 2014 "*spent a considerable amount of time discussing the potential that Gulf of Maine cod is responding to a regime shift in the environment.*" This discussion was in part driven by the recent severe downward trend in recruitment that coincided with a substantial warming trend in the Gulf of Maine. The review panel expressed an interest in seeing an assessment model that included this environmental variability, however previous assessment working groups have concluded that the available analyses were inadequately developed for use in the assessment model. Similar discussions have occurred with GB cod. This proposal is intended to address these concerns.

We recognize that the broad field of using environmental correlates to predict and understand recruitment has been appropriately criticized on a number of grounds (e.g. Myers 1998), including: 1) failure to report, and account for statistically, multiple tested hypotheses, 2) selective publication of only positive correlations, 3) the lack of empirically tested mechanisms, and 4) the use of assessment recruitment and spawning stock biomass time series without accounting for assessment uncertainty. Within the NEFSC, modified assessment models have been developed that directly integrate environmental indices and their uncertainty into the stock recruitment function. Our emphasis on developing a new data set on larval feeding, and evaluating the zooplankton abundances actually experienced by the larvae from each stock, is intended to ensure that the indices we develop are biologically relevant. Various factors lead us to hypothesize that decadal-scale changes in the zooplankton community on the Northeast shelf contribute to cod and haddock recruitment variability, but we recognize that a valid and publishable conclusion will be that recruitment is not associated with this variability.

DELIVERABLES

- Analytical code and approach to developing early life stage stock-specific zooplankton indices from paired ichthyoplankton/zooplankton sampling.
- Zooplankton and temperature indices for evaluation in the four stock assessments.
- Attendance of an oceanographer and ecologist at the assessment meetings.
- Peer-reviewed publications, 1) comparing larval cod and haddock feeding success and diets in the two stocks, and 2) evaluating the effects of variability in larval environment and feeding success on the synchrony/asynchrony of recruitment in the four stocks.

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