Incorporating Environmental and Ecological Variables
to Improve Stock Assessments:
An Application to Northern Shrimp in the Gulf of Maine

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Year 2 Request: NEFSC: $5,000, U Maine: $87,265, ASMFC: $0, Total (Y2) = $92,265
Background

Northern shrimp (Pandalus borealis, hereafter “shrimp”) are primarily distributed in boreal and subarctic waters of the North Atlantic Ocean. The GOM’s shrimp population is considered a single stock unit (ASMFC 2004, 2009, 2012), and the southwestern Gulf of Maine (GOM) is the southern end of the species range. Shrimp are hermaphroditic, maturing first as males at about 2.5 years old, transforming to females at about age 3.5 years and generally not surviving past age 5 in the GOM (ASMFC 2009). The fishery, managed by Atlantic States Marine Fisheries Commission (ASMFC), targets females in winter as they come inshore to hatch their brood.

Abiotic factors, particularly temperature, appear to influence a number of aspects of shrimp life history (ASMFC 2004). The timing of egg development, egg survival, embryonic development, and larval size are linked to incubation temperature (Brillion et al. 2005), and in recent years the start of the hatch period in the GOM has become earlier as temperatures have warmed (Richards 2012). During the six months of egg development, embryos rely on yolk reserves for their nutritional needs and the efficiency of yolk conversion is reduced at higher temperatures (Brillion et al. 2005). Koeller (2000) found that on the Scotian Shelf, shrimp landings and recruitment seemed to be controlled by temperature, habitat availability, and predator biomass. Richards et al. (2012) found that temperature significantly affected the stock-recruitment relationship for the GOM shrimp, with higher recruitment produced under cooler temperatures.

Predation is another factor thought to strongly influence shrimp population dynamics. In a meta-analysis of 9 populations of shrimp, Worm and Myers (2003) found evidence of top-down control by Atlantic cod predation in 8 of the 9 populations. The exception was the GOM, a system where a number of other predators are important in addition to Atlantic cod. Estimates of shrimp biomass consumed by predators in the Gulf of Maine were equal to or greater than the total shrimp biomass estimated by the assessment model under different assumptions of natural mortality (Link and Idoine 2009). These results suggest that incorporating predation in the assessment model is important.

GOM shrimp has been assessed using the Collie-Sissenwine (catch-survey, CSA) model (Collie and Sissenwine 1983; Cadrin et al. 1999) since 1997. CSA has been criticized for being too simple to quantify the complex shrimp life history and demography, especially the sex/size structure, which can be considerably altered by selective harvesting of females. To address these shortcomings, a new length-structured model (LSM) has been developed for shrimp in the GOM (NEFSC 2014). The new model takes advantage of detailed demographic information available for shrimp, and has the following six components: (1) a set of length-structured models to quantify the population dynamics; (2) a logistic model describing size-specific stage transitions from juveniles and males to females; (3) a set of observational models linking state-space variables in the population models with observations made in the fishery and fishery-independent sampling programs; (4) statistical estimators (maximum likelihood and Bayesian) for parameter estimation; (5) models for estimating biological reference points; and (6) projection models.

The LSM was presented as the base model in the shrimp benchmark stock assessment in 2014. However, the results derived from all the stock assessment models including CSA and LSM were rejected by the review panel because of significant residual patterns in model fitting (NEFSC 2014). The review panel recommended further development of LSM with incorporation of environmental and ecological variables to improve the model fit (NEFSC 2014). This project addresses the need for explicit consideration of environmental and ecological variables in the shrimp stock assessment.

Approach

We have the following 3 goals for this proposed FATE project: (1) develop and evaluate approaches for explicit incorporation of temperature in modeling recruitment dynamics in the length-
structured model; (2) evaluate various functions to link temporal variability of shrimp predator abundance with natural mortality; and (3) evaluate impacts of temperature on the growth of shrimp and develop a temperature-dependent growth transition matrix for the length-structured model.

Building on the preliminary study we have done so far, we will complete the following tasks: (1) continue analyzing existing information to examine the relationships between temperature and recruitment; (2) quantify the relationships between temperature and growth; (3) develop and evaluate different functional relationships to link predator abundance with shrimp natural mortality; (4) develop and incorporate likelihood functions based on the models developed above in the length-structured model; and (5) evaluate impacts of incorporating temperature and predators on the quality of the stock assessment in both simulations and the assessment (e.g., retrospective errors and uncertainty).

We plan to complete the project in two years. We will finish the first four tasks (1-4 listed above) in the first year and task (5) in the 2nd year. In the 2nd year, we will also prepare all the software and data to fully incorporate the results derived in this study in the next shrimp stock assessment.

Data availability
Stock assessment data: Several ongoing fishery independent surveys have been conducted in shrimp habitat areas in the GOM, starting as early as 1963. Information from these surveys will be used to develop the necessary biological (shrimp abundance, distribution, population structure) and environmental data (temperature, predator abundance) for incorporating ecological variables in the length-based model. The surveys include the Northeast Fisheries Science Center’s autumn (1963-present) and spring (1968-present) surveys, the ASMFC summer shrimp survey (1984-present), and the Maine Department of Marine Resources (MDMR) summer shrimp survey (1968-1983). In addition, daily sea surface temperature recorded at Boothbay Harbor, Maine is available since 1905 and inshore surveys have been conducted by Maine and NH since 2003; these data represent conditions in nearshore waters where juvenile settlement and early growth occurs (Shumway et al. 1985).

Port sampling of the shrimp fishery has been conducted since 1980 to estimate size and life history stage of the landings. Samples were collected according to a proportional sampling scheme, thus ports handling the greatest volume of shrimp were the most heavily sampled (see Moffett et al. 2011 for further detail). The fishery is conducted primarily during the winter, and thus provides data on shrimp size and stage during a time when surveys are not conducted. Ecological and life history (e.g., growth and maturation) data derived in previous studies (e.g., Haynes and Wigley 1969; Clark and Anthony 1980; Stevenson and Pierce 1984; Shumway et al. 1985; Apollonio et al. 1986; ASMFC 2009, Richards et al. 2012) will also be used.

Estimation of predation pressure on shrimp: Data from food habits sampling during NEFSC spring and autumn surveys will be used to estimate predation pressure on shrimp and scale natural mortality rates in the model. Consumption of shrimp by 10 predators was estimated for SAW 45, but the analyses excluded a number of important predators because they were not sampled early in the time series (Link and Idoine 2009). For the 2014 benchmark assessment (NEFSC 2014), the food habits data were used to calculate a simple predation pressure index (PPI) that was used to scale natural mortality rates (M). To derive the PPI, annual biomass indices for each predator were weighted by the % frequency of occurrence of shrimp in each predator’s diet and then summed across predators to derive an annual index that takes into account both the biomass of the predators and how heavily they appear to prey on shrimp. \( PPI_{is} = \sum_j B_{ij} \times P_{js} \); where PPI = predation pressure index, \( i = \text{year}, s = \text{season}, j = \text{predator species}, B = \text{biomass index}, P = \text{proportion of stomachs containing Pandalids.} \) The approach will be further-developed in this project, including examining appropriate functional forms of the relationship between the PPI and M. We propose to revise and update the predation analysis as part of this project.
**Link temperature to recruitment:** Annual recruitment to a fish stock tends to be highly variable because of large fluctuations in survival during early life history stages (Cushing 1971), potentially related to climate variability (Stige et al. 2013). Large recruitment variability of shrimp in the GOM has been found related to changes in thermal habitats (Richards et al. 2012). Thus, we would like to test the hypothesis that an explicit incorporation of temperature into the shrimp stock-recruitment (SR) relationship within the assessment model can reduce the assessment uncertainty. In this study, the following SR functions (Quinn and Deriso 1999) in conjunction with temperature variables will be built within our length-structured assessment model as possible options to be evaluated:

\[
R_{t+2} = \alpha S_t^\gamma e^{\sum_{i=1}^{n} \delta_i X_i}
\]

(1)

\[
R_{t+2} = \alpha S_t e^{(-\beta \delta + \sum_{i=1}^{n} \delta_i X_i)}
\]

(2)

\[
R_{t+2} = \frac{\alpha S_t}{1 + \beta \delta} e^{\sum_{i=1}^{n} \delta_i X_i}
\]

(3)

where \(R_{t+2}\) is recruitment in year \(t+2\), \(S_t\) is spawning stock biomass (SSB) in year \(t\) (recruitment observed in a given year is a function of spawning biomass observed 2 years previous), \(\alpha, \beta, \) and \(\delta\) are parameters to be estimated, \(X\) is the temperature variables. Two approaches will be used to apply these functions: (a) using these functions to calculate recruitments in the dynamic model (i.e., predicted recruitment is determined by both spawning stock biomass and temperature variables); (b) using these functions to calculate "observed" recruitments and then tuning the model-predicted recruitments which are calculated without temperature variables in the dynamic model. Parameters of these functions could be estimated from both approaches. The above approach is based on an SSB-R function, we will also apply an approach with recruitment being estimated independently of SSB in the model (Chen et al. 2005), but annual deviation of recruitment estimated in the model being linked to the temperature (Maunder and Watters 2003). Assessment results derived from these different approaches will be compared to examine their performance regarding model fitting. Simulation studies will be conducted to test the hypothesis that uncertainty can be reduced if temperature effects on shrimp recruitment dynamics are considered. A "true" fishery and population dynamics of shrimp will be constructed with temperature effects on recruitment dynamics being incorporated. The following simulation scenarios regarding recruitment dynamics in estimation will be tested: (I) ignore temperature effects; (II) mis-specify the environmental SR function; and (III) correctly specify the environmental SR function. Estimated SSB from each simulation scenario will be compared to the known "true" value by using the following formula,

\[
REE = \sqrt{\frac{\sum_{i=1}^{N} (SSB_{estimated} - SSB_{true})^2}{SSB_{true}}}
\]

(4)

Another relevant issue is that recruitment dynamics may be related to an identified regime shift (Richards et al. 2012), suggesting that the environmental SR function could be different in distinct population and climate states. We plan to split the whole time series into two periods (warm period and cold period) to test if the environmental SR relationship differs for the two distinct climatic periods. Finally, stock projections will be done to inform management of shrimp under different scenarios of climate change.

**Link predator abundance to natural mortality:** Although many studies have identified the potential bias of stock assessment caused by erroneous assignment of natural mortality (e.g., Mertz and Myers 1997; Deroba and Schueller 2013), natural mortality of shrimp has been assumed to be constant over time and ontogeny in the assessment. In the proposed study, the assumption of constant natural mortality of shrimp could be be relaxed by linking predator abundance to size-specific and time-varying natural mortality built into our length-structured assessment model. The predation mortality for a given predator and year is modeled as (Hollowed et al. 2000):
\[ M_p = qE e^{-l(\frac{U_{max}}{U_{max}} - 1)} \]  

where \( E \) is the predator effort or abundance, \( q \) is a proportionality constant, \( U_{max} \) is the total amount of food that a unit of predator could have consumed in a given year, \( U \) is the anticipated predation per unit predator effort, \( l \) is the parameter that sets the degree of curvature corresponding to different Holling types (Holling 1965). This approach allows a threshold storage capacity for consumed prey (satiation point), as the shrimp abundance increases to stock size beyond the satiation point, then the effective effort of the predator declines (Hollowed et al. 2000). Main predators will be selected to calculate the predation mortality, and the addition of uncertainty in predator abundance (\( E \)) is modeled using a stochastic term (\( \varepsilon \)). Additional sources of natural mortality for shrimp will be considered as a constant (\( M_c \)) plus to predation natural mortality. A vector for weighting different sizes is applied to the total natural mortality multiplicatively. Thus, natural mortality for a given size class (\( l \)) and year (\( t \)) can be modeled as:

\[ M_{t,l} = \left( M_c + \sum_{j \text{ predators}} q_j E_{j,t} e^{-l\left(\frac{U_j}{U_{max}} - 1\right)}\right) * W_l \]  

This function for linking predator abundance to natural mortality will be developed for shrimp within the assessment model, suggesting natural mortality could be potentially estimated and the assumption of constant natural mortality could be relaxed. By comparing the assessment outputs under different natural mortality scenarios (i.e., with and without linking to predation), the effects of predation on assessment of shrimp could be understood quantitatively.

**Link temperature to growth:** Growth and development rates of shrimp are likely to be affected by their thermal habitats. For a length-structured assessment model, the growth model is usually one of the most important components influencing the model performance (Chen et al. 2005). Explicit incorporation of temperature effects on growth could improve assessment model performance and reduce assessment uncertainty, especially for a species sensitive to temperature. In this study, the von Bertalanffy growth function used to develop the growth transition matrix will be linked to water temperature using Rosso's function which describes the influence of water temperature on the growth coefficient, \( k \). This relationship was expressed as (Rosso et al. 1995):

\[ k(T) = k_{opt} \frac{(T-T_{min})(T-T_{max})}{(T-T_{min})(T-T_{max})-(T_{opt})^2} \]  

where \( T \) represents temperature, \( T_{min} \) is the minimum temperature, \( T_{max} \) is the maximum temperature and \( k_{opt} \) is the optimal growth coefficient at the optimal temperature, \( T_{opt} \). This function will be built into our length-structured assessment model for shrimp. Comparing the assessment results with and without temperature effects incorporated in growth can quantify impacts of temperature effects on growth.

**Develop likelihood functions in the stock assessment model:** Temperature effects will be linked to shrimp recruitment and growth, and predator abundance will be linked to natural mortality. All these functional relationships will be incorporated within our length-structured assessment model, essentially considering temperature and predator abundance as additional input data. We will develop likelihood functions for these data in parameter estimation. Recruitment, natural mortality and the growth coefficient are assumed to follow log normal distributions. Thus, a log likelihood function for each of these life history processes can be expressed as:

\[ -\ln L(\theta | D^{obs}) = \prod_{t=1}^{n} \frac{1}{\sigma \sqrt{2\pi}} e^{\frac{[\ln(D_{t}^{obs}) - \ln(D_{t})]^{2}}{2\sigma^{2}}} \]  

where \( D^{obs} \) is the "observed" recruitment, natural mortality or growth coefficient which could be calculated based on those functional relationships, and \( D \) is the relevant model estimate.
**Collaboration between ASMFC, NEFSC and University of Maine:** We will work with the ASMFC Northern Shrimp Stock Assessment Committee (NSSAC; PIs Richards and Drew are members) to develop a series of simulation scenarios to evaluate impacts of incorporating environmental variables in the stock assessment. All the PIs have been involved in the 2014 benchmark assessment, which will provide the platform for collaboration on data compilation, model development, and results interpretation.

**Outreach**
We will regularly update the ASMFC NSSAC on progress. The results from this study will be presented at industry meetings (e.g., Maine Fishermen’s Forum), at Maine DMR and at scientific conferences. Our goal is to assure that that the approach is well-understood and becomes included in future ASMFC shrimp assessments. We also plan to present the results at a NAFO/ICES Northern Shrimp Assessment Group (NIPAG) meeting, where all other Atlantic northern shrimp stocks are assessed. A webpage will be developed for the project. All the PIs will be involved in the outreach.

**Benefits**
The 2014 review panel for the shrimp benchmark assessment rejected all model-based assessment results due to poor performance of the models in recent years (NEFSC 2014). Failure to consider the effects of ecosystem changes such as temperature and predation is thought to have contributed to poor performance of the models. Given substantial changes already observed in the GOM ecosystem, this project will fill a critical need by developing an assessment model that specifically includes environmental and ecological drivers. The project will investigate specific mechanisms for temperature and predation effects, i.e. temperature effects on growth and recruitment, and predation effects driving annual estimates of natural mortality (M), all to be included and tested in the assessment model. This study will not only improve our understanding of shrimp-habitat-ecosystem dynamics in the GOM, resulting in improved forecasting of recruitment and future productivity, but, will be applicable to other fishery resources in this rapidly changing environment. The successful completion of this project by the end of 2016 will be very timely as the moderate 2013 shrimp year class will be entering the fishery in 2017 (the fishery will likely be closed until 2017). As no assessment models are currently approved for use in management, the need is great.

**Deliverables**
We will be working closely with ASMFC NSSAC to maximize the utility of the results for shrimp stock assessment and management. We will develop models, computer programs and a user manual for incorporating temperature and predator abundance in the shrimp stock assessment. A final report will be produced to document the data compilation, model configurations and scenarios considered in the assessment. The indicators and any other relevant data developed for the project will be made available for posting on the FATE central website, and the metadata will be uploaded to the NMFS Data Catalog and Metadata Repository. *Models and computer code developed in this project will be made available and support will be provided to include them in the NOAA Fisheries Toolbox.* At least two peer-reviewed scientific papers will be published describing the model, its application to shrimp and results of incorporating temperature and predation. We expect this model to be part of the 2016 and subsequent annual stock assessments for shrimp. The successful completion of the project will likely trigger a benchmark assessment for shrimp, as currently no models are approved for use in management.
References


