A Bayesian State-Space Approach to Improve Projections of Stock Biomass for Managing New England Groundfish

a) Brief summary of the work to be completed

Specification of Allowable Biological Catch (ABC) requires projecting biomass one to three or more years beyond the terminal year of fish stock assessments. However, these projections are often highly uncertain and perform poorly under retrospective review. For many stocks, consistent biases in assessments, known as retrospective errors, have led to overestimation of biomass resulting in unintentional overfishing, sharp reductions in catch quotas, and decreased stakeholder confidence in the management process (Brooks & Legault 2016, Wiedenmann & Jensen 2017). Such issues present a need for a new methodology that can better quantify uncertainty in biomass estimates and improve prediction performance. To this end, the proposed work will develop a Bayesian state-space model aimed at improving projections of fish stock abundance. Generalizable across species and systems, this modeling framework will focus on taking advantage of existing methods and data sources, including assessment model outputs, federal and state fishery-independent survey information, and catch data, to forecast biomass and provide a probabilistic definition of associated scientific uncertainty. The approach will also allow for the inclusion of climate information, expert input, and inference from similar species, where appropriate, to make full use of all data available to inform stock projections. To test the efficacy of the approach, performance of the developed model will be evaluated for three data-rich and three data-limited New England groundfish stocks by comparing the prediction-error variance in each case to current projection methods based on stock assessments. The results of this work will then be openly shared with assessment scientists through the development of an R package to implement the proposed modeling strategy such that it can be applied broadly in the management of marine fisheries.

b) Rationale for the proposed activity

Since its first passage in 1976 and through subsequent revisions, the Magnuson-Stevens Act has provided the regulatory framework to preserve living marine resources and the economic activities that they support through its mandate that management bodies prevent overfishing, rebuild overfished stocks, and ensure a sustainable seafood supply into the future (MSA 2007). In pursuit of these goals, fisheries scientists conduct stock assessments, generally every one to four years, in which fishery-independent survey data are combined with catch information to assess the status of harvested fish stocks and recommend ABC levels for the following years (NMFS 2001, ASMFC 2009, Wiedenmann & Jensen 2017). Although such survey and harvest data are compiled annually (ASMFC 2009, Politis et al. 2014), the ABCs set during the last assessment are typically maintained until resources allow for an operational or benchmark stock assessment update (NMFS 2001). If the most recent survey and catch data are consulted to adjust harvest levels, fisheries scientists are often limited to less formal consideration of data from the prior year to inform biomass projection one to two years ahead. Without a designated model in place beyond the stock assessment for updating abundance estimates, such intermediate forecasts are often challenging and have high prediction error that can contribute to regulatory volatility, ratcheting down of catch quotas, increased risk of overfishing, and degraded stakeholder confidence in the assessment process (Glaser et al. 2014, Brooks & Legault 2016, Szuwalski et al. 2017).

Perhaps most problematic for scientists and stakeholders is when such assessment errors develop into consistent, retrospective patterns (Brooks & Legault 2016, Szuwalski et al. 2017). Defined by Mohn (1999) as "systematic inconsistencies among a series of estimates of population size based on increasing periods of data", retrospective errors are typically the result of data errors or misspecification of life history parameters for the target fish stock (Szuwalski et al. 2017, Wiedenmann & Jensen 2017). These patterns often manifest as an overestimate of spawning stock biomass and an underestimate of fishing mortality in the prior assessment (Brooks & Legault 2016, Wiedenmann & Jensen 2017), leading to catch advice suggesting that an ABC higher than should actually be set will allow a stock to meet management targets in the coming years (Figure 1). When the status of the stock is updated, however, it is found that those quotas were unintentionally set too high and future harvest needs to be significantly reduced to avoid a population decline. For example, a retrospective pattern was recently identified in the stock assessments being used to manage the Gulf of Maine Atlantic cod (*Gadus morhua*) stock. After assessment models suggested that this population was increasing during the late 2000s, subsequent updates revealed that the stock was being overfished and was in decline. Catch quotas were immediately and significantly cut in an effort to reverse this trend, resulting in consequential economic impacts for the regional fishing industry (NEFSC 2015, NMFS 2017, Wiedenmann & Jensen 2017).

Due to the potentially substantial negative effects and ubiquity of projection errors in fish stock assessment (Brooks & Legault 2016), much recent work has focused on the issue. A robust simulation exercise conducted by Deroba et al. (2015) found that assessment models currently in use tend to diverge from the true biomass values in the most recent years of the data time series. In addition, Brooks & Legault (2016) and Wiedenmann & Jensen (2017) concluded that accurate estimates of terminal assessment year and first projected year biomasses are most important to reducing forecast error and providing accurate catch advice. These findings suggest a consistent possibility for prediction errors or retrospective patterns and may make avoidance of biomass projections altogether an attractive alternative. However, Wiedenmann & Jensen (2015) found that setting ABCs based only on the terminal assessment year biomass, discounted a priori for assumed overestimation, still led to unsatisfactory results. Even in the absence of accurate estimates of stock biomass and its future trajectory, many authors have also stressed the importance of developing full, quantified accountings of scientific uncertainty in assessments (Berkson et al. 2011, Punt et al. 2011, Deroba et al. 2015, Maunder & Piner 2015, Chyrsafi & Kuparinen 2016). In doing so, catch advice and Annual Catch Limits (ACLs) can be developed to reflect the degree to which the population dynamics and status of a given fish stock are understood and can be precisely projected.

In summary, there is a clear need in fisheries science for methods that can pair with existing stock assessments to both reduce error in stock projections and quantify the scientific uncertainty inherent to those predictions in order to improve the catch advice used in the management process. Where assessment models have historically focused on developing quantitative explanations of available biological data (Cooper 2006), the present work will seek to develop a flexible modeling framework that leverages all existing data sources to attempt to reduce biomass prediction error and provide a probabilistic definition of the uncertainty in abundance estimates. In achieving either or both of these goals, this effort will help to reduce regulatory risk and stabilize catch quotas as is desired by both scientists and industry stakeholders alike.

c) Scientific or technical objectives and/or hypotheses to be tested

With the primary objective of fully characterizing uncertainty in and improving projection of stock biomass levels, this work will focus on developing a Bayesian state-space modeling methodology. Within this broad and flexible class of models, many techniques, including non-parametric models and dynamic linear modeling methods such as Kalman filtering, will be explored to identify the approach best suited to forecasting fish stock abundance. These candidate methods will be pursued in the Bayesian paradigm, determined by past work to be well-suited for modeling fish population dynamics in that it allows for the incorporation of prior knowledge and expert input (Fronczyk et al. 2012, Maunder & Piner 2015, Chrysafi & Kuparinen 2016), accounts for and accurately quantifies different sources of uncertainty in parameter values and posterior point estimates (Fronczyk et al. 2012, Magnusson et al. 2013, Maunder & Piner 2015), provides a convenient way to make use of all available data sources (Chrysafi & Kuparinen 2016), and builds inference based on probabilistic modeling (Fronczyk et al. 2012, Maunder & Piner 2015).

For example, a recent assessment report was drafted for the New England Fishery Management Council by Rago (2017) focusing on Atlantic halibut (*Hippoglossus hippoglossus*), a stock for which available data is limited to highly variable catch estimates and regional and coastal fishery-independent surveys. Here, the author developed a change forecasting algorithm, termed the First and Second Derivative model, based on the observed rates of change in relative abundance indices. While this was determined to be the best option for management among the evaluated approaches, it was concluded that more research and testing is required. Further, the author recommended that future work for halibut, or other similarly data-limited species, could improve estimation of stock trajectories through use of Kalman filtering or other state-space modeling techniques that better incorporate information about overall observation error while maintaining sufficient flexibility for signal detection. Therefore, these findings support the exploration of state-space methods in this work as a promising way forward in trying to project fish stock biomass, define the scientific uncertainty involved, and provide sound catch advice even when data are limited.

The biomass projection method developed here is intended to be broadly applicable for both age-based and index-based stock assessment scenarios. While the focus of the model inputs will be incorporating existing assessment outputs, federal and state fishery-independent surveys, and catch data, a protocol to utilize all available information, including expert input and environmental data, will also be generated as recommended by previous work (Punt et al. 2011, Fronczyk et al. 2012, Maunder & Piner 2015, Szuwalski et al. 2015, Chrysafi & Kuparinen 2016, Szuwalski & Hollowed 2016). Test cases to evaluate performance and determine the optimal model form will be drawn from the Northeast Multispecies Complex, for which retrospective errors in stock projections have been prevalent and impactful (Brooks & Legault 2016 Wiedenmann & Jensen 2017). Specifically, modeling efforts will focus on three age-based stocks, Southern New England/Mid-Atlantic yellowtail flounder (*Limanda ferruginea*), Acadian redfish (*Sebastes fasciatus*), and white hake (*Urophycis tenuis*), and three index-based stocks, Georges Bank Atlantic cod, Georges Bank yellowtail flounder, and witch flounder (*Glyptocephalus cynoglossus*).

The developed state-space modeling approach will then be compared with the currently employed methods used for the New England groundfish case study stocks both in simulation and with the most recent assessment data to determine if it represents an improvement in prediction ability. First, the utility of the probabilistic definition of uncertainty surrounding biomass estimates given by the state-space model in developing catch advice will be evaluated. By providing the information in a probabilistic fashion, assessment scientists would better be able to account for uncertainty in their catch advice, potentially leading to more risk-averse ACLs. Second, the prediction errors for each of the chosen groundfish stocks will be contrasted between the state-space model and the estimation models used in recent assessments through a "retrospective forecasting" method similar to that of Brooks & Legault (2016). The results of these model diagnostics will then be published and the state-space methods developed will be written into a package in R. By making the modeling approach available and easily implemented in an opensource software, it will be broadly accessible to fisheries scientists in a variety of systems facing challenges in projecting stock biomass for the setting of harvest quotas.

d) Methodology

To develop the Bayesian state-space modeling framework for projecting fish stock biomass, test data with a known "true" state must first be created. Because biomass estimates given by stock assessments can have significant uncertainty and may even be biased as a result of modeling assumptions (Brooks & Legault 2016, Szuwalski et al. 2017, Wiedenmann & Jensen 2017), a projection method that recreates assessment values well may not produce satisfactory results when implemented in management. Therefore, simulated population data must be used here to accurately assess the performance of candidate state-space models, determine the optimal approach, and compare predictive ability to currently employed methods like the Age Structured Projection Model (AGEPRO) (Brodziak et al. 1998). Specifically, six simulated fish stocks with life history characteristics matching the peer-reviewed stock assessment values for the chosen case study groundfish will be generated using the PopSim tools provided in the NOAA Fisheries Toolbox made available by NOAA Fisheries' Office of Science and Technology (http://nft.nefsc.noaa.gov). Analysis will begin with the simpler index-based case, where assessment of data-limited species typically focuses on survey observations and catch data in order to project terminal year and one-year-ahead biomass (NMFS 2001, Rago 2017).

For the index-based groundfish stocks, Bayesian state-space models will be fit to generated survey and catch information representative of what is available in such management scenarios and assessed in their ability to project biomass up to three years beyond the end of the training data series. Candidate models will be fit to the simulated time series by utilizing the biomass estimate, parameter estimates, and their associated variances at time t as prior distributions to combine with new information that comes available for projecting biomass at time $t+1$ (Figure 2). Here, different state-space techniques will be applied to the simulated data to determine the model form that performs best in projection via retrospective forecasting and compares favorably to the assessment models currently in place for each candidate stock. In contrast to modern assessment models that seek to optimize goodness of fit to raw biological data (Cooper 2006), development of this approach will focus on using assessment model outputs, survey data, harvest data, and other available information to provide the best stock projections. Model selection will focus solely on the minimization of prediction error, in line with efforts shown to better forecast stock levels in other fisheries (Deyle et al. 2013). With the state-space model form determined, the developed projection method will then be applied to the "real-world" stock assessment data available to fisheries scientists and compared in forecasting to the methods in use. Here, advantages and disadvantages of the Bayesian state-space model will be evaluated through the changes in catch advice it would have provided to the setting of ACLs during past assessments of stock status.

After an optimal state-space model is identified for the index-based cases, a more complicated model of the same general form will be developed for the age-based scenarios. Similar to the approach taken for the index-based stocks, the model will first be constructed on the simulated age-structured data using the accepted life history parameters for the three chosen age-based New England groundfish test cases. Here, cohort abundances, growth information, and recruitment estimates from the simulation will be used to project future stock biomass with uncertainty surrounding parameter estimates incorporated in the form of prior distributions. Throughout the modeled time series, new survey data, stock assessments, and other information will be used to perform Bayesian updates of biomass estimates in the same manner as described for the index-based projections. Once again, model fits will be evaluated by their performance in minimizing prediction error compared to the assessment models currently in use via retrospective forecasting of the simulated data. When the optimal age-structured model strategy is identified, it will then be applied to the "real-world" data for the age-based groundfish case-study stocks and compared to the predictive ability of the present operating models used in their respective stock assessments. Performance will be judged on the success of the state-space model in providing biomass projections and definitions of uncertainty that would have led to improved catch advice for New England groundfish during recent assessment updates for each stock. Based on these results, the strengths and weakness of the developed method in projecting biomass will be assessed and reported.

e) Relevance of results

The proposed use of Bayesian state-space modeling in projecting fish stock biomass presents several potentially useful characteristics. In allowing prior information and direct statements of uncertainty to be incorporated into estimates of parameters like natural mortality, assessment scientists will be able to develop catch advice based upon probabilistic inferences of current biomass as is true of some currently utilized approaches. In data-limited stocks, these methods also provide a convenient way to use expert input and information from other similar species (Punt et al. 2011) to provide more informed estimates of abundance. Further, changes in regulation, abnormally large recruitment classes, or other known disturbances to stocks can be adjusted for in the model through the inclusion of interventions at the relevant time steps to improve prediction. Perhaps most valuably, Bayesian methods could provide a convenient and simple way to update biomass estimates with new information between stock assessments without devoting significant staff resources or needing to refit a peer-reviewed model (Figure 2). Here, fisheries scientists could set annual ABCs with consideration of the most recent survey and catch information and avoid projections of biomass more than one year into the future altogether. In total, these characteristics will allow for the incorporation of all available data for a given fish stock, provide probabilistic statements of scientific uncertainty to be considered in developing catch advice, and potentially reduce the magnitude of errors in the estimation and projection of stock biomasses made in the development of ABC levels.

Errors in stock assessment present challenges for management and impact the fishing industry throughout the United States. Of particular concern are cases where consistent overestimation of stock biomass has led to unintentional overfishing and set back efforts to rebuild declining stocks (Brooks & Legault 2016, Szuwalski et al. 2017). Prevalent in New England (Wiedenmann & Jensen 2015, Brooks & Legault 2016), but also present in all systems and assessment methods, such error patterns have had tangible, negative impacts on a regional seafood industry that supports over 100,000 jobs and contributes approximately $5 billion to the regional gross domestic product annually (NMFS 2017). In striving to develop better catch advice and buffer against such errors, the present work will contribute to maintenance of stable catch quotas and decreased regulatory risk that will benefit both fisheries scientists and industry stakeholders. By providing the developed modeling method(s) in an R package with associated documentation, fisheries scientists will have open access to what may prove a valuable tool in meeting the management goals first mandated decades ago by the Magnuson-Stevens Act.

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Figures

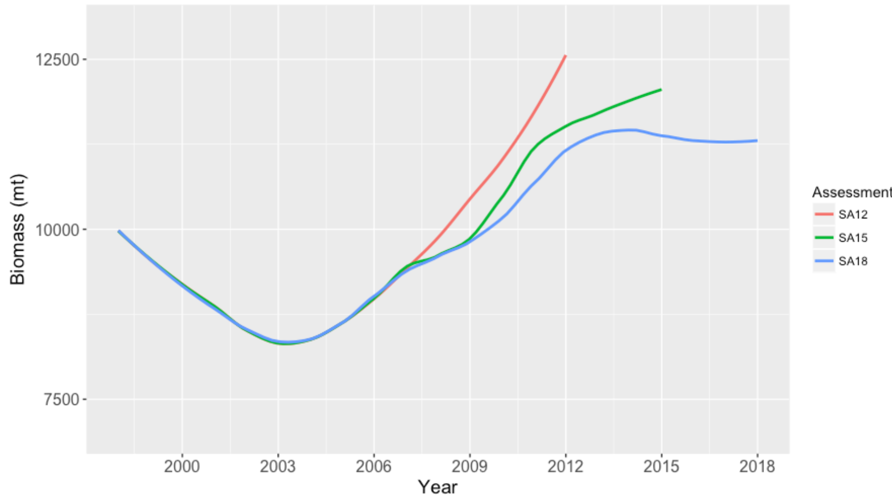

Figure 1: Biomass trajectories for a hypothetical groundfish stock estimated by assessments performed in 2012 (SA12, red), 2015 (SA15, green), and 2018 (SA18, blue). A retrospective pattern has resulted in consistent biomass overestimation that is likely to result in poor catch advice being incorporated in the development of ABC levels.

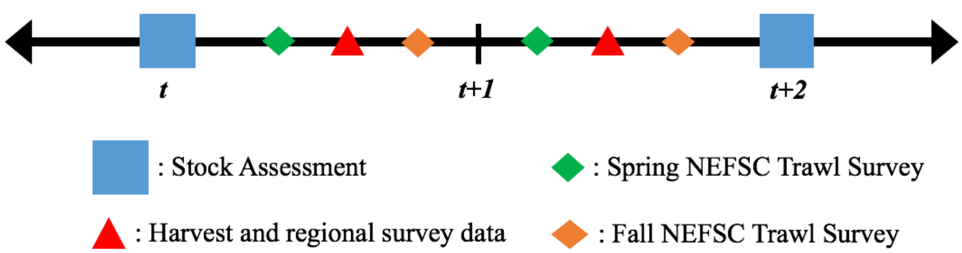

Figure 2: A timeline depicting the schedule of information used to manage a hypothetical New England groundfish stock. Between a benchmark and operational stock assessment in years *t* and *t+2*, respectively, the Northeast Fisheries Science Center (NEFSC) performs spring and fall bottom trawl surveys and collects catch and other survey data annually. If fisheries scientists were trying to set catch levels for the coming year at *t+1*, the current approach would rely on a biomass estimate and ABC set in the stock assessment at time *t* with limited consultation of information collected in the intervening year. The modeling method proposed here would incorporate each survey and catch estimate as it came available through Bayesian updating, allowing a previously peer-reviewed model to modify estimates of current biomass used to set harvest levels throughout the interval between formal assessments of stock status. This updating is intended to be simple enough that it can be performed quickly by either assessment scientists or technical support staff, such as the Groundfish Plan Development Team for the New England Fisheries Management Council, without taking resources away from development of assessments for other species.