1. **Title: Incorporating recruitment-environment linkages into stock assessment models for Alaskan groundfish with application to population projections in a changing climate**

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Background

Recruitment and other population processes of groundfish in the Gulf of Alaska (GOA) and Bering Sea-Aleutian Islands (BSAI) have well-documented linkages to indices of environmental forcing and variability, such as the El Niño Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO), sea surface temperature and height, and sea ice extent (e.g. Hollowed et al. 1987, Bailey and Picquelle 2002, Clark and Hare 2002, Mueter et al. 2007, Doyle et al. 2009, Hunt et al. 2011, Vert Pre et al. 2013, Stachura et al. 2014). Synchrony in recruitment trends among species with similar early life history traits suggests environmental conditions can influence recruitment for many species simultaneously, and has been found among groups of species in the GOA, BSAI, and elsewhere (e.g. Hollowed et al. 1987, Doyle et al. 2009, Link et al. 2009). Stachura et al. (2014) identified synchrony in recruitment among GOA flatfish species (including Pacific halibut) that move from the slope to nursery grounds on the shelf as larvae; the study linked recruitment of these flatfish to an environmental index heavily driven by sea surface height (SSH).

The effects of a warming climate have been measured in both the GOA and BSAI ecosystems. Temperatures on the southeastern Bering Sea shelf increased by approximately 3 degrees from 1997-2007 (Stabeno et al. 2007), accompanied by declines in the extent of sea ice, changes in the timing of sea ice retreat, and changes in the timing and species composition of zooplankton availability (Hunt et al. 2011). To understand the possible consequences of climate effects on fish productivity, population dynamics, and fisheries, we need effective modeling and statistical tools to infer and select among plausible relationships between population processes and environmental conditions. These models can then be used to forecast population dynamics under future climate change and harvesting scenarios (Hollowed et al. 2009).

Integrated statistical catch-at-age (SCA) models are powerful tools for modeling fish population dynamics that can be fit to multiple data types simultaneously (Deriso et al. 1985, Maunder and Punt 2013). Fitted SCA models can be used to forecast population dynamics under future environmental and fishing scenarios. Previous studies have used SCA models to address the effects of recruitment-environment linkages on the performance of assessments and management strategies (e.g. Maunder and Watters 2003, Haltuch and Punt 2011, Punt et al. 2014). Studies have also used estimated annual recruitment deviations from SCA models to evaluate recruitment-environment linkages by fitting stock-recruitment relationships that incorporate environmental variables to these estimated recruitment deviations (Wilderbuer et al. 2013). Previous studies have not, however, addressed how best to choose among competing SCA models with different functional relationships between recruitment and the environment.

Model selection methods are not commonly used to choose among competing SCA models (exceptions include Wilberg and Bence 2008, Linton and Bence 2011, Maunder and Harley 2011). This is because for commonly applied model selection tools (e.g. Akaike's Information Criterion, AIC, Akaike 1974), the "effective" number of parameters cannot be clearly specified. Recent studies have shown potential for the analysis of retrospective patterns, cross-validation, and the Deviance Information Criterion (DIC) to select among competing SCA models that differed in their representation of selectivity or catchability (Wilberg and Bence 2008, Linton and Bence 2011, Maunder and Harley 2011, Martell and Stewart 2014).

Although recruitment-environment linkages could be modeled outside of an SCA framework where model selection is more commonly applied, there are several advantages to using SCA models. First, a broader scope of analyses is possible within an SCA model. Simulation studies

can be easily expanded to consider relationships between environmental conditions and catchability, growth, and natural mortality. These multiple linkages can then be simultaneously included in forecasts along with harvest policy evaluations. Second, estimation uncertainty can be propagated easily in projections, accounting for the sources of error attributed to each data component. Third, multiple data sources included within an SCA model may contain information about recruitment-environment linkages. Non-integrated approaches that use estimated recruitment deviations from an SCA model may overstate accuracy, ignore covariance structure, and imply that the assessment model used to estimate recruitment is mis-specified. An SCA model that includes a recruitment-environment linkage and is fit to the same data as an equivalent model that ignores such linkages may estimate a different recruitment time-series, as well as different values for other model parameters and derived quantities (such as spawning biomass). This may affect conclusions about the recruitment-environment linkage (even assuming the same functional form when using an integrated and non-integrated approach) and impact model projections. Fitting SCA models with and without recruitment-environment linkages may be a better way to learn about those linkages than non-integrated approaches, given that it is possible to correctly select among competing SCA models. Incorporating recruitment-environment relationships into SCA models and simulation-testing the ability of model selection tools to choose among those models will help to identify robust approaches for improving methods for forecasting fish population dynamics under plausible future climate conditions.

An important role of forecasting population dynamics is to evaluate the potential for alternative harvest policies to meet fishery and management objectives, given uncertainty about both population dynamics (Cooke 1999) and future environmental conditions (A'mar et al. 2009, Walters and Parma 1996). A'mar (2009) and Walters and Parma (1996) showed that some harvest policies may be more robust to future environmental uncertainties than others. Likewise, forecasts under some harvest policies may be less sensitive to mis-specification of recruitment-environment relationships than others.

In this study, we will use simulations to develop stock assessment models that incorporate hypothesized relationships between recruitment and environmental indices and we will evaluate the accuracy of model selection tools to distinguish among these relationships. Results from the simulation study will inform best practices for including recruitment-environment linkages in a suite of stock assessment-based forecasts for GOA flatfish, including Pacific halibut. Our objectives are (1) to improve forecasts of fish population dynamics given hypotheses about future climate change and fishing by identifying robust tools for model selection, and (2) to evaluate the potential for alternative harvest policies to meet management objectives over a range of future climate scenarios, using forecasting models that incorporate correctly- and mis-specified linkages between population dynamics and environmental conditions.

Approach

We will investigate methods for including recruitment-environment relationships in SCA models for life history types relevant to Alaska flatfish species, and evaluate the ability of a suite of model selection tools to choose the correct models using Monte-Carlo simulations. We will apply results from the simulation study to model recruitment-environment linkages for a suite of GOA flatfish species, including Pacific halibut, that exhibit planktonic larval transport from the slope to nursery grounds on the shelf ("cross-shelf transport") and appear to exhibit positively correlated recruitment with an environmental index related to SSH (Stachura et al. 2014).

Stachura et al. (2014) developed environmental indices using PCA to group correlated environmental variables into uncorrelated principal components. This study will build on Stachura et al. (2014) by using the same environmental indices found to be related to synchronous recruitment patterns among "cross-shelf transport" flatfish to model recruitment-environment linkages in flatfish assessment models.

Next, we will evaluate the importance of selecting SCA models that specify recruitment-environment linkages correctly when conducting forecasts under a range of harvest policies and future climate scenarios. Forecasts will be made for a suite of Intergovernmental Panel on Climate Change (IPCC) climate scenarios under current North Pacific Fishery Management Council (NPFMC) and International Pacific Halibut Commission (IPHC) harvest policies. The impact of modeling a correctly- or mis-specified recruitment-environment linkage on the results of SCA forecasts will be evaluated for each harvest policy and climate scenario.

Modeling recruitment-environment linkages and evaluating methods for selecting among models

Monte-Carlo simulation includes the following steps: (i) developing an operating model (OM) to represent the true state of the population, (ii) simulating the process of gathering data from the population with observation error, (iii) conducting a stock assessment on the data generated in step (ii), (iv) evaluating the ability of the stock assessment to estimate relevant quantities such as spawning biomass by comparing estimated values to corresponding true values from the OM, and (v) repeating steps (i)–(iv) many times to account for observation and process error. This project will include an additional step in which model selection criteria will be applied to the stock assessments.

Stock Synthesis (SS3) is a flexible SCA modeling platform that is frequently used to conduct stock assessments (Methot and Wetzel 2013). SS3 will be used as an OM and an assessment model using the R package ss3sim (Anderson et al. 2014a,b; CRM is a co-author). The package ss3sim is already programmed to conduct Monte-Carlo simulations to evaluate fisheries stock assessments. A minimal amount of programming will be required to update ss3sim such that an OM and a stock assessment can include a recruitment-environment linkage. The SS3 framework allows the user to specify relationships between an environmental index and a population parameter (Methot and Wetzel 2013). We will evaluate models with a multiplicative environmental linkage to either (a) the parameter determining mean unfished recruitment (Stewart and Martell 2014), (b) the parameter determining stock productivity (steepness), or (c) the annual recruitment deviations (Schirripa et al. 2009). These methods assume that environmental conditions are known without error. We will also evaluate an alternative method that includes an environmental index as a data source linked to recruitment through a likelihood component (Schirripa et al. 2009); this method accounts for observation error associated with the environmental index.

The model selection tools that will be evaluated are: DIC, Mohn's retrospective statistic, and hold-out cross-validation. Each of these tools has performed well for selecting the model that produces the least biased estimate of biomass among SCA models with differing assumptions about selectivity (Maunder & Harley 2011, Linton & Bence 2010) or catchability (Wilberg & Bence 2008). These three model selection tools have different selection criteria. The DIC balances between model fit and the effective number of parameters and requires integration of the Bayesian posterior distribution (Spiegelhalter et al. 2002). Cross-validation methods arise from non-parametric statistics and involve fitting models using a subset of the data and evaluating predictions for the data that were omitted (Maunder and Harley 2011). Mohn's

retrospective statistic arises from stock assessment problems and is designed to evaluate the magnitude of retrospective bias (Mohn 1999).

Four sets of scenarios will be considered, each of which are predicted to influence the ability of assessments to estimate quantities of interest and the ability of model selection methods to choose the correct model. First, the consequences of including (or not) a recruitment-environment linkage in the assessment model when such linkages do (or do not) exist in the OM will be evaluated. Second, data quality and quantity scenarios will be modeled because the amount of age-composition data and characteristics of ageing error are known to influence estimates of recruitment. Simulations will be conducted for three data quality categories that are characteristic of the available data for Alaska groundfish species. Third, fishing and biomass history influence the amount of information in the data on productivity and other parameters. Three biomass histories will be considered: a "one-way trip" where biomass declines consistently over time, a constant biomass scenario, and a scenario where biomass initially declines and then recovers. Lastly, multiple assumptions about the characteristics of environmental indices will be modeled. Stachura et al. (2014) used PCA analysis to group environmental indices in the GOA and BSAI into uncorrelated principle components that were then used to relate recruitment to environmental conditions. We will use the variance and autocorrelation properties of the environmental indices in Stachura et al. (2014) to develop test environmental indices. Simulations will test the implications of modeling the wrong environmental index, and also the effect of the percent of recruitment variation explained by an environmental index in the OM.

Forecasting to explore the performance of harvest policies under future climate trajectories and alternative models of recruitment-environment linkages

The Monte-Carlo simulations described above will create stock assessments fitted to data generated from the OM that (1) correctly or incorrectly specify an existing recruitment-environment linkage, (2) incorrectly specify a recruitment-environment linkage where none exists, or (3) incorrectly specify that there is not a recruitment-environment linkage when one, in fact, exists. Forecasts will be conducted using the population dynamics of some of these stock assessments for a halibut-like and a contrasting flatfish-like species and data scenario, and for several alternative harvest policies and future IPCC climate scenarios.

To specify the environmental conditions associated with the set of climate scenarios, we will calculate the same index related to SSH that Stachura et al. (2014) found to be related to synchronous recruitment success among flatfish. This simulated environmental index will be calculated based on simulated data resulting from projections under IPCC climate scenarios from a subset of global climate models appropriate for the region (e.g. Hollowed et al. 2009, Ianelli et al. 2011, Sheffield et al. 2013). We will use CMIP5 simulations of the future climate based on the Representative Concentration Pathways (RCP) 8.5 scenario. This scenario features relatively high greenhouse gas concentrations and large changes in the global climate. The climate model data will be downloaded from the website maintained by the Program for Climate Model Diagnosis and Intercomparison (http://cmip-pcmdi.llnl.gov/cmip5/). Full suites of oceanographic and meteorological variables are available towards applying the approach of Stachura et al. (2014). The result will be a 6-10 member ensemble of time series of the environmental index spanning the expected range of probable outcomes that will be used in the stock assessment models. We will apply the harvest policies currently used for GOA flatfish species as specified in the GOA Fishery Management Plan (NPFMC 2013), as well as the policy

currently applied to Pacific halibut in the GOA. The harvest policies for species included in the GOA FMP vary by the amount of information available to conduct assessments and the perceived reliability of assessment results. The IPHC applies a constant exploitation rate policy to GOA Pacific halibut equal to the estimated value for F_{MSY} (Stewart and Martell 2014).

Performance measures for harvest policies, including trajectories of future biomass and stock status, catches, and inter-annual variation in catches, will be compared among forecasts using assessment models that were fitted to the same data and thus originate from the same "true" population dynamics (the same OM configuration). The magnitude of differences between forecasting results for a particular OM configuration based on assessments with different assumptions about recruitment-environment linkages will therefore be evaluated. By further comparing forecast results across climate scenarios we will address the degree to which variation in management performance measures can be attributed to model uncertainty in assumed specification of recruitment-environment linkages and to uncertainty in climate predictions.

Benefits

This proposed study is unique in that it will compare the ability of model selection tools to choose among hypotheses about recruitment-environment linkages included in SCA models. Use of model selection tools to choose among SCA models is not common and this will be the first study to compare the ability of DIC, Mohn's statistic, and cross-validation methods to identify the correct SCA model. We will therefore provide guidance on the use of model selection tools for SCA models incorporating recruitment-environment relationships, offering the potential for improved ability to forecast fish population dynamics under a variety of future climate scenarios and harvest policies. Our project will assess the sensitivity and robustness of forecasts to correct and incorrect representations of recruitment-environment linkages, and evaluate the expected performance of current fisheries harvest policies for flatfish in the GOA, given uncertainty in model specification and climate scenario prediction. This study will therefore improve upon tools for linking recruitment and environmental conditions within stock assessments.

SCA models such as SS3 are commonly used for stock assessments nationally and internationally. Our work to understand the effectiveness of model selection tools that can be used with SCA models to explore model specification uncertainty has broad assessment applications beyond incorporation of recruitment-environment linkages. The further development of the ss3sim R package to conduct the work in our proposed study will result in a modeling framework that could be used and expanded to explore: (1) other population-environment linkages such as environmental effects on growth rates, (2) the evaluation of harvest policies using a full Management Strategy Evaluation (MSE), and (3) forecasting and MSE testing when accounting for technical interactions, such as limitations to catching several species of GOA flatfish in the groundfish trawl fishery due to halibut bycatch.

Deliverables

The project will result in a Master's thesis for a student supervised by Dr. Gavin Fay at the University of Massachusetts Dartmouth, with Dr. Carey McGilliard serving as a thesis committee member. The project will also expand the R package ss3sim to include the ability to explore recruitment-environment linkages in simulation studies about the performance of stock assessment models. Two peer-reviewed publications will be produced. The first paper will present the results of the simulation study to test the efficacy of the model selection methods. The second paper will conduct the forecasting under the IPCC scenarios. Results will be disseminated at scientific meetings, including the 2016 and 2017 annual FATE meetings.

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