Title: Effects of climate-driven ecosystem change on Atlantic salmon growth and survival at sea: analyses of West Greenland salmon

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Effects of climate-driven ecosystem change on Atlantic salmon growth and survival at sea: analyses of West Greenland salmon

Background

In the Northwest Atlantic, increases in marine mortality of Atlantic salmon during the 1990s aligned with a phase shift in population productivity (Chaput et al. 2005). These declines in abundance and productivity occurred coherently in time over the full North American range of the species from Maine to Labrador (Mills et al. 2013). The spatial and temporal coherence observed in population downturns points towards marine conditions as exerting a strong influence on survival and population dynamics (Mills et al. 2013).

Atlantic salmon have a complex life history: they remain in freshwater through their juvenile phase, undertake extensive oceanic migrations, and generally spend one to three years at sea before returning to freshwater to spawn as either one sea-winter, two sea-winter, or three sea-winter adults (Thorstad et al. 2011). Population declines are most significant for the multi sea-winter life history type, which primarily includes the larger female spawners (Chaput 2012). North American Atlantic salmon that are destined to be multi sea-winter adults congregate and feed off west Greenland in the summer and overwinter in the Labrador Sea (Reddin 1988, Thorstad et al. 2011). While freshwater life stages are influenced by local conditions, their time on overwintering and feeding grounds can expose Atlantic salmon from widely distributed stocks to common marine ecosystem conditions. Correlation analyses have identified climate and ecosystem factors such as warming ocean temperatures and changes in salmon prey – particularly capelin – as closely linked to Atlantic salmon survival and productivity (Mills et al. 2103), but the mechanisms behind these relationships remain undiagnosed.

The influence of ecosystem conditions on Atlantic salmon population dynamics has previously been recognized in the ICES stock assessment, and for a number of years, the ICES models used a metric of thermal habitat in the northwest Atlantic to forecast pre-fishery abundance and provide catch advice for the West Greenland fishery (ICES 2001). However in 2001, this relationship broke down and the forecast model predicted a sharp increase in pre-fishery abundance. The catch advice urged extreme caution in harvest decisions to avoid significant overexploitation, as little information was available to confirm this improvement in pre-fishery abundance. Subsequent population monitoring and assessment efforts suggest that this prediction of increased pre-fishery abundance was inaccurate. This environmental variable has not been used in subsequent assessments. One reason for its demise was the lack of a clear mechanistic understanding of how the environmental variable influenced Atlantic salmon marine productivity and abundance.

Growth provides one mechanism through which ecosystem changes can affect Atlantic salmon survival and productivity. Many of the ecosystem changes that have been correlated with population declines can influence the energy available to salmon. Warmer waters increase metabolic demand and may cause salmon to migrate further to favorable thermal habitats (Taboada and Anadon 2012, Minke-Martin et al. 2015). At the same time, the prey base for Atlantic salmon has become less energetically valuable, particularly as capelin have declined in availability and condition and as zooplankton communities that support the pelagic food web have shifted towards less lipid rich species (Mills et al. 2013; Renkawitz et al., *in press*). These same ecosystem process have been hypothesized to have impacted the productivity of numerous other marine species such as the common murre (*Uria aalge*, Davoren and Montevecchi 2003), Atlantic cod (*Gadus morua*, Mullowney and Rose 2014), and the Northwest Atlantic harp seals (*Phoca groenlandica*, Hammill et al. 1995).

Previous studies have found positive correlations between growth and survival in European populations of Atlantic salmon (Peyronnet et al., 2007, McCarthy et al. 2008, Friedland et al. 2009a), but this relationship has not held for North American populations (Friedland et al. 2005, Friedland et al. 2009b, Hogan and Friedland 2010). However, these studies have several notable limitations that preclude a full understanding of how ecosystem conditions are related to growth and how growth influences marine survival. First, these studies have focused on post-smolt growth through the first sea winter; thus, limited data are available to examine the patterns, causes, and consequences of growth changes during later portions of the marine life phase. Further, these studies have all relied on analyses of growth from scale samples obtained from salmon that have returned to their natal rivers; as such, they are inherently biased by observing only the survivors. Thus, relationships between ecosystem conditions, growth, and survival may be misinterpreted if there are substantial differences in growth patterns between survivors and non-survivors.

Approach

Salmon stocks from across North America aggregate to feed off of West Greenland during the summer months (Sheehan et al. 2010), where they have been subjected to a significant mixed-stock fishery since the early 1960's (Jensen 1990). The Greenland stock complex has been well monitored and sampled annually since 1969, with the exception of 1977, 1993, and 1994 (ICES 2015). The Greenland samples are particularly valuable for studying changes in growth and relationships to ecosystem conditions because they represent a broader suite of fish than just those that survive to return to their natal rivers to spawn.

Though this work, we seek to understand Atlantic salmon growth as a mechanism linking ecosystem conditions to population outcomes. Key questions to be examined include:

- Have growth characteristics of North American Atlantic salmon changed over time?
- Do distinct growth patterns emerge in the Greenland fish that may be related to 'survivors' versus 'non-survivors'?
- Are variations in growth indices related to oceanographic and ecosystem conditions?
- Are variations in growth related to population abundance and productivity?

Growth data collection

Scales and associated biological characteristics (e.g. length and weight) from Atlantic salmon have been sampled from the mixed North American stock that feeds at West Greenland since 1969. Over 60K scales are currently inventoried and stored by the Department of Fisheries and Ocean's Northwest Atlantic Fisheries Center in St. John's, Newfoundland. We will sample 75 scales from each year (when adequate sample sizes are available), for a total of approximately 3500 scales. These 75 scales will be selected from samples that were classified as North American in the continent of origin assessment via scale characteristics discrimination methods (1969-2001) or genetic assignment (2002-2014). We will develop a stratified random sampling design that incorporates *freshwater/smolt age* (to ensure representation of fish across the North American population range, Chaput et al. 2006) and *month* (to spread representation over the sampling season) as stratification factors.

A standard set of growth data will extracted from all sampled scales via an image analysis system. Measurements will include such things as total scale radius, distance from scale radius to all circuli, distance from scale radius to all annuli, and distance from scale radius to the end of the freshwater zone. From these data, growth metrics such as total and seasonal marine growth will be calculated. All scale measurement data will be collected according to the protocols outlined by the Workshop on Age Determination of Salmon (ICES 2011). In addition to acquiring the above growth reference points, age data (i.e., freshwater age, marine age, total age and virgin sea age (for repeat spawners)) will be verified or recorded if missing. All data will be audited according to NEFSC Atlantic Salmon Research and Conservation Task (ASRCT) procedures. Measurement data will be stored in *SalmoScale*, a master database maintained by the ASRCT for archiving all scale measurements produced by the Task. Metadata will be developed and published in *InPort*, the NMFS Data Catalogue and Metadata Respository.

Analyses

1. *Have growth characteristics of North American Atlantic salmon changed over time?*

Changes over time in individual growth measurements will be analyzed using several techniques, including (1) linear regression against time to examine trends, (2) changepoint or regime shift analysis to identify major shifts in the time series, and (3) piecewise or multiphase regression to assess the importance of shifts versus trends in characterizing temporal changes. In addition, chronological cluster analysis will be applied to the multivariate suite of growth metrics to identify major periods of time that are characterized by unique growth conditions.

2. *Do distinct growth patterns emerge in the Greenland fish that may be related to 'survivors' versus 'non-survivors'?*

Principal components analysis (PCA) and cluster analysis will be used to evaluate whether distinct growth patterns emerge for groups of fish in the Greenland samples (e.g. high versus low growth groups or steady growers from seasonal growers). These methods will first be applied to the multivariate growth data over the full time series. To capture temporal changes in distinctions between growth patterns, we will also impose time periods of interest based on (1) the timing of growth changes documented by the changepoints or chronological cluster breaks identified in #1 and (2) a chronological clustering of Atlantic salmon population metrics developed in Mills et al. (2013).

Any distinct growth patterns observed in the Greenland fish will also be compared to growth patterns of 'survivors' that returned to rivers to spawn. We are currently measuring and analyzing these data from Penobscot River fish and have initiated a collaboration to collect growth data from a New Brunswick (Canada) salmon population. Both resulting datasets will be available for comparative analyses to the Greenland scales before year 2 of this project.

3. Are variations in growth indices related to oceanographic and ecosystem conditions?

A suite of oceanographic and ecosystem factors used in Mills et al. (2013) will be used to assess correlations with Atlantic salmon growth metrics, including climate indices (i.e., North American Oscillation, Atlantic Multidecadal Oscillation), physical conditions (i.e., sea surface temperature, sea surface salinity), and lower trophic level biological conditions (i.e., phytoplankton abundance, zooplankton community composition, and capelin size). In addition, several new time series (e.g. metrics of temperature and plankton phenology in the Labrador Sea, distance to certain thermal habitats, and degree day indices) are being developed in support of a separate project and will be available for use within this effort. Correlation analysis that accounts for lags and temporal autocorrelation will be used to identify climate, oceanographic, and ecosystem features that are associated with individual growth metrics or multivariate growth patterns (from questions 1 and 2 above) and to identify the lags that are relevant to each pairwise relationship. Ecosystem factors that frequently emerge as significant in the correlation analyses will be incorporated into a multiple regression model to evaluate suites of factors that provide the best statistical models of Atlantic salmon growth.

4. *Are variations in growth related to population abundance and productivity?*

Atlantic salmon population data will be compiled from stock assessment estimates of (1) abundance of fish before Aug 1 in a given year (termed "prefishery abundance" (PFA) because the date aligns with a time before they encounter the fishery off West Greenland) and (2) productivity as indexed by scaling the PFA in each year by the number of contributing spawners (Chaput et al. 2005; ICES 2007, 2012). Both of these metrics were used in Mills et al. (2013) and are updated with each annual stock assessment (ICES 2015). The same approach described in #3 above will be used to evaluate correlations between growth metrics and Atlantic salmon abundance and productivity. Also similar to #3, we will use a multiple regression approach and model selection techniques to identify suites of growth factors that can be used to model Atlantic salmon population characteristics.

Benefits

The proposed work will elucidate how environmental and ecosystem factors affect growth of Atlantic salmon and evaluate the role of growth as a mechanism mediating population productivity and marine mortality. This endeavor directly aligns with several FATE priorities, most closely with topics 1 and 6 in the RFP. Specifically, our work will test hypotheses to understand the role of growth in linking environmental conditions to salmon populations. By considering lags in environmental influences, we will potentially identify a means of using observed conditions in the stock assessment model to predict future population trajectories. It also contributes to topics 3 and 4 in the RFP, as the research will shape our understanding of how climate and ecosystem change influence trophic regulation of population productivity in the Northwest Atlantic, identify important drivers (indicators) linking climate to population dynamics, and elucidate the role Atlantic salmon may play as an indicator of large-scale changes in the North Atlantic.

The types of information that will be developed through this project are essential for better protecting a species that is listed as endangered under the Endangered Species Act in the United States (65 Federal Register 69469, 17 November 2000, 74 Federal Register 29344, 19 June 2009) and that has experienced population declines throughout its North American geographic range (Chaput et al. 2005, Mills et al. 2013). The information also directly responds to critiques that have arisen in review of the stock assessment model since 2010. Reviewers of that assessment expressed a concern over "the lack of progress in developing a predictive capability that includes an environmental driver related to marine survival" (ICES 2010). Since that time, the North Atlantic Salmon Conservation Organization (NASCO) has asked ICES to consider: "The influence of environmental variables on productivity should be investigated for incorporation into the model…" (ICES 2012). In 2015 NASCO continued to seek this information by requesting ICES to "report on any developments in relation to incorporating environmental variables in these models" (ICES 2015). Through this project, we will seek a clear mechanistic relationship between environmental variables and Atlantic salmon marine productivity and abundance. We will also identify lags between environmental conditions, growth responses, and population impacts that would provide a solid foundation for incorporating environmental information into the Atlantic salmon stock assessment.

As a whole, the proposed work will address the following NEFSC Strategic Science Plan (2016 – 2021) Themes/Foci: (i) Sustainable Fisheries—Improve quality, efficiency, and responsiveness of stock assessments and other science based advice, (ii) Protected Resources—Improve quality, efficiency, and responsiveness of stock assessments and other science based advice, and (iii) Science in Support of Ecosystem-Based Fisheries Management—Improve understanding of the influence of climate, ecosystem, habitat factors, and species relationships on living marine resource dynamics in order to provide integrated scientific advice to managers. The proposed work ultimately seeks to reform the stock assessment process for Atlantic salmon, in response to the request of management, through the inclusion of climate, ecosystem, and habitat considerations. Developing an understanding of the influences of ecosystem variables and processes on Atlantic salmon abundance and productivity will inform options for incorporating ecosystem variables into international stock assessment and forecast models.

Deliverables

Deliverables of this project will provide data, information, and results to both science and management audiences through a variety of outputs. We believe the results will provide valuable broader insights into how ecosystem conditions can affect biological processes and fish population dynamics. As such, we will seek to communicate the results from this project beyond the Atlantic salmon audience. The following deliverables will result from this work:

- The scale measurement database from this this project will be archived and maintained within SalmoScale, a master database maintained by NOAA's ASRCT for archiving all scale measurement data produced by the Task. Its use will ensure that the data collected are comparable to scale growth measurements collected via other efforts and it will allow for data to be easily shared with current and future collaborators interested in questions related to Atlantic salmon growth.
- A working paper will be presented to the ICES Working Group on North Atlantic Salmon outlining the results of the project and assessing the potential for incorporating environmental variables into the stock assessment models and forecast projections used to produce catch advice as requested by NASCO. Subject to the timing of the award, the working paper is expected to be presented at the Working Group's 2018 Annual Meeting.
- Results of this project will be presented at numerous domestic and international scientific conferences. A presentation will be given at the Atlantic Salmon Ecosystems Forum (2018), and if a suitable session exists we will present at the ICES Annual Science Conference (ASC, 2018). Both of these targeted venues are attended by scientists and managers involved in the assessment and management of Atlantic salmon. If a suitable session exists does not exist at ICES ASC, an alternative high profile meeting will be sought. Preliminary and final results will also be presented at the 2017 and 2018 FATE meetings, and other low-/no-cost opportunities for regional presentations will be sought.
- The results of this project will be submitted for publication as a peer-reviewed paper. The manuscript will describe the ecosystem drivers affecting Atlantic salmon marine growth and productivity and identify opportunities for incorporating environmental variables into stock projection models.

Timeline

In year 1, a sampling design will be developed and scales will be obtained and prepared to align with this design. Scale data collection will begin in year 1 but will extend into year 2. Data analyses, results synthesis, and product development will be completed in year 2.

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