Annual report for Phase I of "A spatially-explicit ecosystem model for quantifying marine mammal impacts on Chinook salmon in the Northeast Pacific Ocean"

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Executive Summary

Over the last decade, models of intermediate complexity (MICE) models have emerged as a tool for addressing tradeoffs between fisheries management and conservation. As marine mammal predator populations have largely rebounded on the west coast of North America, there is an increasing need to use simple ecosystem models to understand the relative impacts of fishing and predation on the natural mortality of commercially valuable species, like Chinook salmon. Our project addresses these questions by integrating data from marine mammal diets, trends in marine mammal abundance, knowledge about the spatiotemporal overlap between predators (marine mammals) and prey (Chinook salmon), and information about the seasonal shifts or migrations that affect these species and interactions. Ultimately, we're interested in using our simplified ecosystem model to ask how adjustments to the food web (either predators like pinnipeds or changes in fishing mortality) might affect Chinook salmon.

Introduction

This report represents an overview of the first phase of the Pacific Salmon Commission funded project by Kaplan et al. "A spatially-explicit ecosystem model for quantifying marine mammal impacts on Chinook salmon in the Northeast Pacific Ocean". Over the last year, we have compiled multiple datasets related to marine mammal abundance and diet, synthesized existing approaches to modeling bioenergetics for marine mammal predators, and implemented a detailed bioenergetics model of Chinook salmon consumption in inland waters.

Phase II of this project will involve expanding the spatial and seasonal complexity of the consumption model. The spatial areas used will be similar to those that have been used for the analysis of coded wire tag recoveries (Weitkamp 2010). We will explore the construction of monthly time steps in our model, and how those temporal periods compare to quarterly (3-month) intervals.

Methods

Diet Data ***(See attached PDF for details and diet summary)***

A number of different methods have been used to previously quantify the consumption of salmonids by marine mammals – examples include observational studies of feeding events, estimating frequency of occurrence in scats, the analysis of stomach content data, indirect measurements (via stable isotope or fatty acid samples), and more recent genetic methods (Scordino 2010). Each of these methods may have inherent selectivity, and the adoption of new techniques has changed through time.

To capture the variation in diet studies, we compiled a large database (> 250 records) of published consumption estimates from the west coast of Canada and the United States, 1930 – present. A more detailed description of the database, as well as summary plots and descriptions, is included as an appendix to this report. In summary, we stratified diet studies by marine mammal predator (Steller sea lion, California sea lion, harbor seal, killer whale), month, spatial location, and data collection methodology. For each record, we also included the sample size and uncertainty of the estimated proportion that both total salmon and Chinook made to the diet of the predator. These sample sizes can then be used to weight each study, so that they can be combined in a hierarchical meta-analysis across regions and time periods. Several studies included in our database are in stages of peer-review, but this database and our code to process it will ultimately be made public.

Abundance and trend data

One of the basic components of our ecosystem model of Chinook salmon consumption is understanding how relative mortality of Chinook salmon has changed through time, particularly as there have been large increases in many marine mammal populations around the world (Magera et al. 2013). We focused our compilation of trends in marine mammal populations on time series available through published literature, or government reports and stock assessments since 1970. Several marine mammal species (killer whales, harbor seals) allowed us to generate estimates at a very fine spatial scale (smaller than state / province boundaries). Others, such as time series of California sea lions are collected at a coarser scale (though most are distributed in California). When possible, we also included seasonal variation in pinniped and killer whale numbers – for example, several hundred male California sea lions overwinter in the Salish Sea, but the majority leave to rookeries in California (S. Jeffries, pers. comm.).

One of the challenges in working with survey count data is that it is noisy, and surveys may not exist for every year. To generate estimates of marine mammal abundance in all years, we developed and applied hierarchical state space models unique to each marine mammal predator. These state space models included estimates of trends and density dependence, as well as process and observation variance for each predator. The implementation of these time series methods was done using the MARSS R package (Ward et al. 2010, Holmes et al. 2012). For surveys with missing observations, we replaced NA values with the state estimate from the Kalman filter, along with associated 95% CIs (Shumway and Stoffer 2006).

Preliminary estimates of marine mammal trends have been completed; one additional promising data source (WDFW at-sea surveys) will likely be included in next few months.

Salmon movement data

One of the challenges in developing a spatially explicit model of Chinook salmon and predators is that we need to develop estimates of movement rates between spatial boxes. Because north-migrating salmon may transition between boxes both as juveniles and adults, we needed to develop movement rates of both juveniles and adults. We've accomplished this using three different approaches. First we compiled catch and effort data from commercial and recreational landings from Alaska Department of Fish and Game, Fisheries and Oceans Canada, and the Pacific Fishery Management Council. The objective of using these data was to determine whether statistical models can be fit to catch and effort data from multiple sectors (gears, commercial or recreational) to improve estimates of movement. A second approach, focused on adult movement rates, was to use coded wire tag databases to recover the spatial and temporal distribution of recoveries (Weitkamp 2010). The objective of this approach was to use the spatial distribution of recoveries for dominant stocks relative to all recoveries as a proxy for adult movement. As a third approach, focusing on juvenile Chinook movement, we are working with observational sampling data collected by DFO (PI Marc Trudel) and NOAA (PI Kurt Fresh and others).

Bioenergetics model ***(See attached PDF for details and plots)***

The synthesis of the diet, predator abundance, and salmon movement data is the bioenergetics model. We begin with a simple one patch model of the Salish Sea to determine the consumption rate of Chinook salmon per year. We have completed a draft bioenergetics model for harbor seals, and expect to complete the models for Steller sea lions, California Sea Lions, and killer whales over the next 4-6 weeks.

For example, using a simplified version of Howard et al.'s (2013) bioenergetics model of Puget Sound harbor seals, we have estimated the annual consumption in terms of numbers of Chinook. As a first pass the model has sex and stage-specific energy needs for the predator (Howard et al. 2013; Table 1), age-specific energy content for the Chinook prey (O'neill et al. 2014; Table 2), the fraction of Chinook salmon in the diet of the predator (see diet review), and a time series of predator abundance (Ward et al. 2011;).

The goal is to estimate the number of Chinook consumed by year and age. Let $E_{i,s,m,y}^{j}$ be the expected monthly energy needs of predator *j*, stage *i*, sex *s,* during month *m* and year *y*. The expected energy derived from Chinook salmon in the diet is

$$EC_{i,s,m,y}^{j} = E_{i,s,m,y}^{j} \times f_i^j$$

where, f_i^j is the fraction of Chinook salmon in the diet. To determine the number of Chinook salmon consumed we must account for the selectivity of the different aged Chinook by the predator ($v_{i,a}^{j}$), and the energy content of the Chinook for a given age (E_a^C).

$$NC^{j}_{a,i,s,m,y} = EC^{j}_{i,s,m,y} \times \frac{v^{j}_{i,a}}{\sum_a v^{j}_{i,a} E^{C}_{a}}$$

The total number of chinook consumed by year and age is found by summing over predators, stages, sex, and month.

$$NC_{a,y} = \sum_{j}\sum_{i}\sum_{s}\sum_{m} NC^{j}_{a,i,s,m,y}$$

Results

Project Deliverables

All deliverables regarding data and consumption model development have been met to date. The only logistical hurdle that has been encountered for this project is that Fisheries and Oceans Canada was not able to provide us with data on fishing effort for most of the years or months included in our data request. Without effort, the remaining catch data is not very informative with respect to Chinook movement. Fortunately, we are also relying on other data sources, such as CWT recoveries, so this will not be a significant issue.

Project Schedule

Despite initial delays in processing contracts (largely at NWFSC), this project is largely on schedule. Brandon Chasco was hired as a contractor to start in fall 2014, and has been working full time since January 2015. A second short term contractor (Jesse Adams) was hired for three months in spring 2015 to assist with database and diet analyses. By the end of summer, we aim to have our summer inland bioenergetics model completed (using R) and will expand that in fall to incorporate other spatial areas and seasons.

QA/QC

The PIs (Kaplan, Ward) and contractors have had weekly progress meetings to evaluate analyses, and anticipate future needs. We've also had monthly updates with other co-PIs on aspects related to their various areas of specialty (B. Hanson, S. Pearson, A. Thomas, M. Ford for diet, A. Acevedo Gutierrez and D. Noren for bioenergetics). We've also reached out to other partners for feedback or assistance with data (K. Fresh, L. Weitkamp).

Monitoring and evaluation

The PIs have held quarterly project meetings to outline progress on deliverables to date. We anticipate that over the next year, we will be able to complete another 2-3 peer reviewed papers at a minimum, as well as disseminate our databases and code.

Benefits

This project has generated several products that will be of value to the greater scientific community. First, we've generated multiple databases (time series of marine mammal trends, detailed database of marine mammal diets) that we will make publicly available through a repository on GitHub. Second, we will complete the detailed bioenergetics model of the Salish Sea in summer months by the end of August 2015. Third, we've generated two peer reviewed papers that are related to and will help inform this work.

The **first attached paper** (Marshall et al. 2015) largely focuses on policy conflicts that arise from managing multiple protected species, particularly when predator populations recover. One of the case studies included for this paper was the killer whale – Chinook salmon – pinniped food web of the greater Northeast Pacific Ocean, in part using abundance time series included as part of our marine mammal trend dataset described above.

The **second attached paper** (Ward et al. 2015, Ecosphere *in review*) integrates population survey data from two geographically isolated populations of killer whales (Southern Resident, and Southeast Alaska Resident populations). Using mark-recapture methods, we examined the correlation between populations, and showed extremely high correlations in demographic rates. The mechanism for these correlations are that both populations appear to be consuming Chinook salmon in summer – specifically Chinook salmon originating from southern rivers in the United States (Templin et al. 2011). Further evidence of diet and Chinook salmon being a likely mechanism for these correlations is that both populations of killer whales have similar contaminant fingerprints (G. Ylitalo pers. comm.). Previous work has shown similar correlations between Southern and Northern Resident whales (Ford et al. 2010), but this work expands the geographic scope of synchrony, and highlights the need to consider the ability of Chinook salmon to correlate top predators across very large spatial scales.

Discussion

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