Final report for JISAO Research Development Award

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Improvement and extension of a northern fur seal bioenergetic model critical to evaluating an ongoing population decline

This award provided funding to support improvement and extension of a northern fur seal bioenergetic model to further fur seal conservation efforts and incorporate them into ecosystem-based fisheries management decisions. This effort primarily built on an existing fur seal bioenergetic model that was funded by the Lenfest Ocean Program. The two objectives of this project were to 1) use data from captive fur seals to refine bioenergetic model parameters, focusing in particular on adult males, and 2) analyze existing fur seal diet data since 1987 to quantify the factors that influence fur seal prey consumption, allowing for the estimation of pollock consumption in previous years where diet data are lacking and facilitating future efforts to operationalize the incorporation of fur seals in the CEATTLE model, a multi-species pollock model. A summary of the work conducted, outcomes, products, and future directions are provided for each objective.

Objective 1: Captive data

I obtained data on body weight, food consumption, and caloric intake from northern fur seals (n = 41) housed at four facilities between 1984 and 2020. Data were obtained from the Seattle Aquarium (Seattle, WA), New England Aquarium (Boston, MA), Mystic Aquarium (Mystic, CT), and the University of British Columbia (UBC)/Vancouver Aquarium (Vancouver, BC, Canada). Animals at UBC participated in research activities, and as such, I also obtained data from satiation trials where seals were offered unlimited amounts of food for 8-hour periods. Data spanned all fur seal age and sex classes, from birth to 25 years of age, and also included nursing pups and reproductive females. Seals were categorized into the following categories for subsequent statistical analysis: nursing pups, weaned pups (non-nursing seals < 1 year), juveniles (ages 1 - 3), subadult males (ages 4 - 7), adult males (ages 8+), non-reproductive adult females (ages 4+), and reproductive females (age 4+ and pregnant or lactating).

Generalized additive mixed models (GAMMs) were used to assess how weight, food consumption, and energy intake varied throughout the year and with age, with separate models run for each variable and demographic group. I also used general linear or linear mixed effects models to describe the relationship between daily average energy intake and daily mass-specific weight change for each group. For the satiation trials, I calculated the percentage increase in food consumption above normal consumption, but limited all comparisons to qualitative and not statistical ones due to limited sample sizes and the confounding issues associated with month.

Overall, the results indicated that fur seals exhibited seasonal fluctuations in weight, food consumption, and energy intake that generally corresponded with the timing of life history events in wild fur seals (Figure 1.1). For example, food consumption and energy intake of adult males was highest in the months leading up to the breeding season and lowest during the breeding season when many adult males are fasting and holding territory. Seasonal fluctuations in food consumption/energy intake often resulted in corresponding shifts in mass, but this was not always the case. Most demographic groups gained relatively more energy in the spring and winter compared with the summer and fall (Figure 1.2), suggesting that seals may experience reduced metabolic costs during certain times of the year.

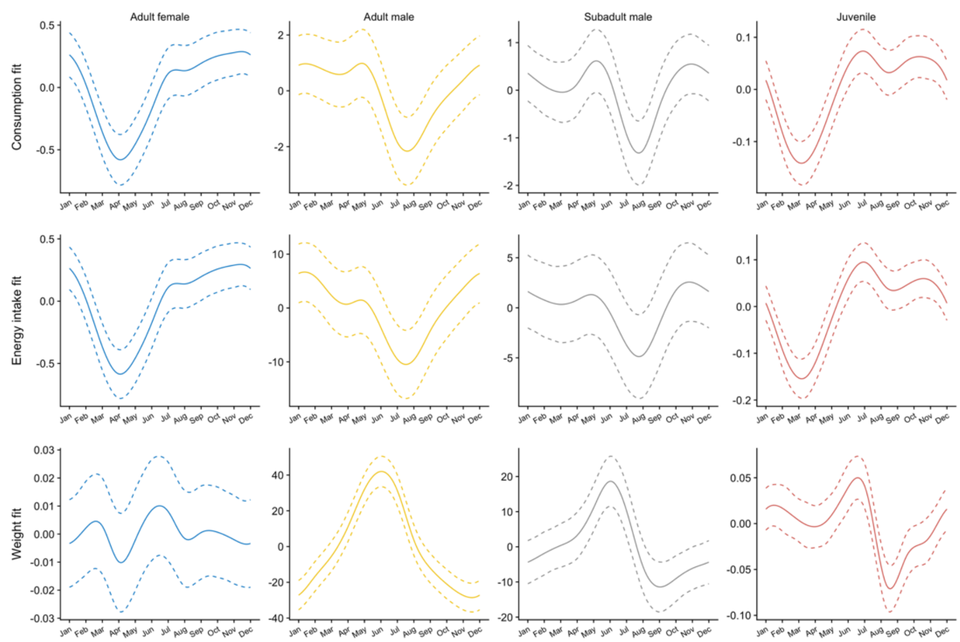

Figure 1.1. Model fits from generalized additive mixed models showing how food consumption, energy intake, and weight of captive adult fur seals changes within the year. Dashed lines represent 95% confidence intervals. The juvenile analyses for food consumption and energy intake and the adult female analysis for weight were conducted after log-transforming the response variable.

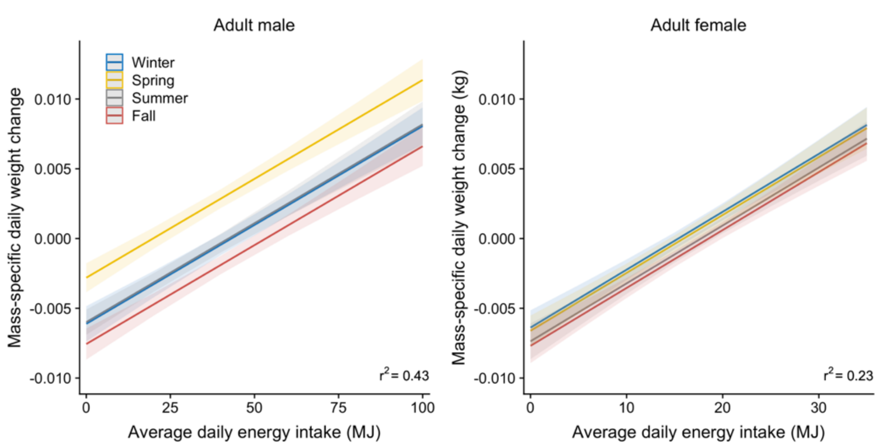

Figure 1.2. The relationship between mass-specific daily changes in weight and average daily energy intake of adult male (left) and adult female (right) captive northern fur seals in four different seasons.

Reproductive females exhibited increases in food consumption/energy intake late in gestation, likely due to the costs of supporting a rapidly growing fetus. During lactation, food consumption was nearly twice that of consumption during early pregnancy (Figure 1.3). This value was similar to food consumption of adult females during the satiation trials, suggesting that lactating females likely need to consume near their maximum amounts to support a pup. Nursing pups experienced relatively continuous gains in mass throughout lactation, with a slight plateau around the time that wild pups molt their lanugo coat (Figure 1.3). Once weaned, food consumption rapidly increased but weight continued to decline, indicating newly weaned pups likely need ready access to abundant food resources soon after departing from the rookery to minimize weight loss during this vulnerable dispersal phase.

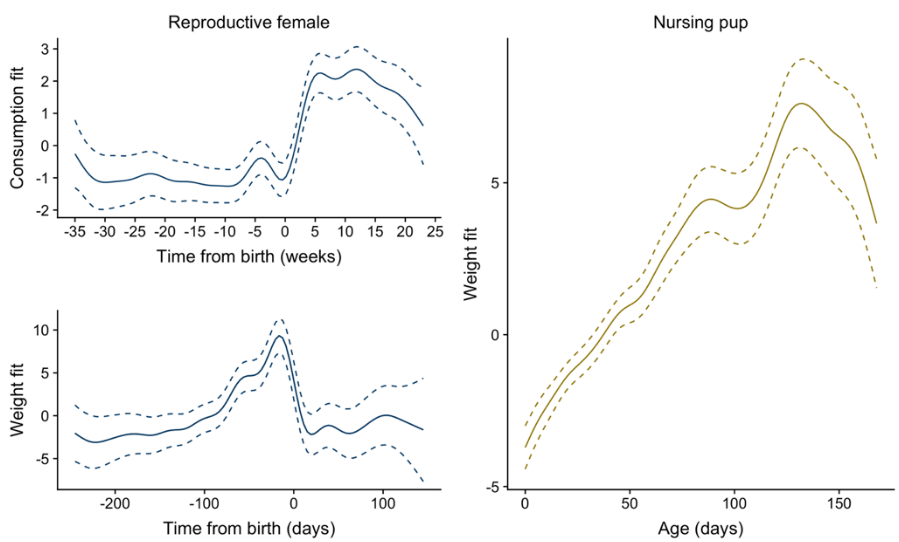

Figure 1.3. Model fits from generalized additive mixed models showing how food consumption and weight of captive reproductive fur seals change with time from birth (left) and how weight of nursing pups changes with age (right). Dashed lines represent 95% confidence intervals. The model fit from the energy intake model was not shown because it was similar to the consumption fit plot.

The results of this objective have been written up as a manuscript to be submitted to Marine Mammal Science titled "Seasonal and age-related variation in weight and prey consumption of northern fur seals (*Callorhinus ursinus*)". The manuscript is currently with co-authors awaiting their comments. The outcomes of this objective fill several critical data gaps for northern fur seals, notably in providing estimates of food consumption for adult males, for which very little empirical data exist, and newly weaned pups during a critical life history stage. In light of these results, we plan to reevaluate the parameter values used in our bioenergetic models to determine if any future changes are needed to better refine the model. We do not have any ongoing plans to estimate food consumption of newly weaned pups; however, this has been an area of interest in the past and the data generated from this effort could be used in such an effort. The inclusion of nursing pup data in our study was unexpected but valuable, as it provides a benchmark for weights and wean masses of apparently healthy pups that data from wild pups can be compared against.

Objective 2: Diet study

Diet data derived from scat and spew samples collected from fur seal rookeries in the Pribilof Islands were provided by NOAA collaborators. Samples were collected across 14 years between 1987 and 2013. I reconstructed the biomass and energy composition of the diet in each year and at each rookery complex using the enumerated prey, reconstructions of prey mass from regression equations between hard part size, length, and mass, and prey energy density estimates from the literature (Figure 2.1). Environmental and walleye pollock data were compiled by from online portals and collaborators, including the annual Bering Sea groundfish bottom trawl survey (https://apps-afsc.fisheries.noaa.gov/RACE/groundfish/survey_data/data.htm), sea surface temperature (SST) and satellite altimetry data (https://psl.noaa.gov/data/gridded/tables/sst.html and https://marine.copernicus.eu/), and the St. Paul Island, AK weather station observations (https://www.ncdc.noaa.gov/data-access/land-based-station-data/station number_ID: USW00025713/Custom GHCN-Daily .csv). These variables included data on temperature (air, SST), wind speed and direction, eddy activity, and rainfall, which were summarized during June 15 - August 24th because this represents the period just prior to when the majority of fur seal diet samples were collected. Additionally, Bering Sea shelf (< 200 meter depth) bottom temperature, pollock numbers and biomass (total, separated into > and < 30 cm bins to represent juveniles and mature pollock), and CPUE data of other fur seal prey species and other pollock predators (arrowtooth flounder and Pacific cod) were obtained from the late June-July survey. Rookery-specific values for each variable were calculated using utilization distribution maps of lactating females derived from satellite tracking data.

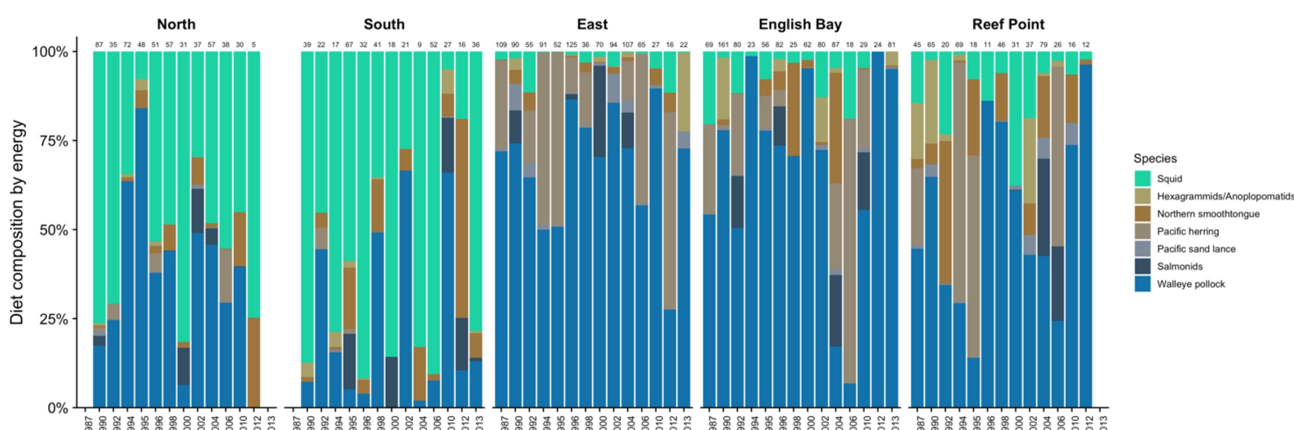

Figure 2.1. Interannual variation in the diet composition by energy of primary prey species/groups consumed by northern fur seals, separated by rookery complex. Sample sizes are shown above each bar.

A variety of statistical approaches were used to visualize the diet data, including non-metric multidimensional scaling (nMDS) and network analysis. I used a multiple regression compositional analysis to determine whether I could predict the diet composition of fur seals (% other prey, % pollock < 30 cm, % pollock > 30 cm). The predictor variables included several of the fish variables described above and the abiotic variables, which were reduced to two uncorrelated variables using a principal components analysis (Figure 2.2). A separate analysis was run for each rookery complex; years where there were less than 30 scat/spew samples collected were excluded from this analysis. Variables were included in the final model based on their significance (p <0.1).

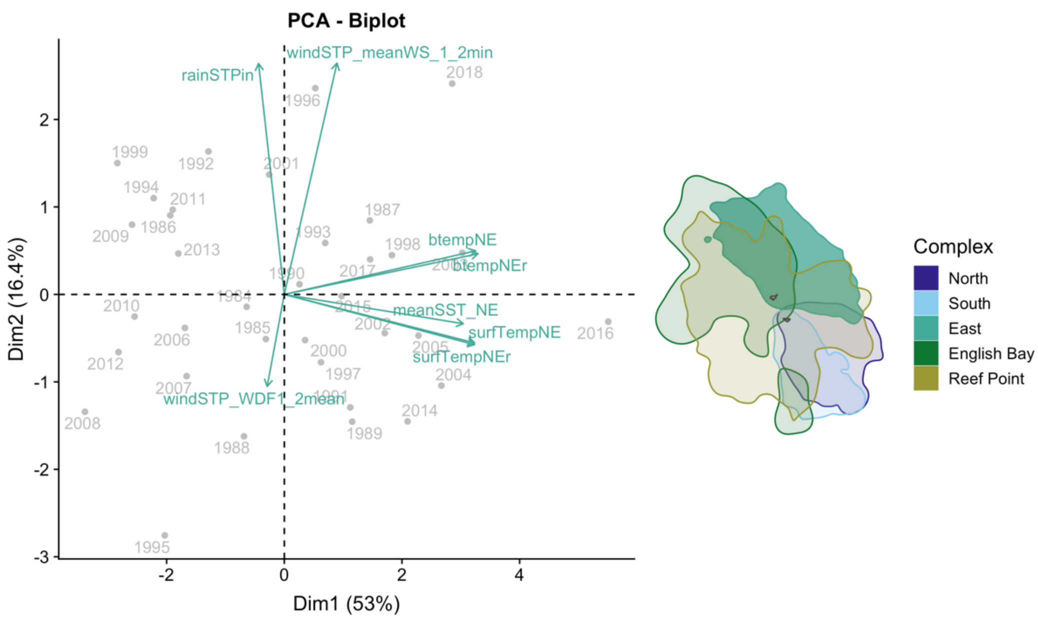

Figure 2.2. The variable loadings and individual years from a principal component analysis of abiotic environmental variables (left). Years were primarily discriminated on the first component by temperature (surface, bottom, and mean SST), and by wind and rain on the second component. Separate analyses were run for each rookery complex because of different foraging ranges of lactating females (right). Here, results are shown just for the East complex on St. Paul Island.

There was separation in diet among rookery complexes, with the greatest differences occurring between complexes on St. Paul Island and St. George Island. Differences between islands were primarily driven by a greater dependence on squid by fur seals from St. George and a greater dependence on fish at St. Paul Island (Figure 2.3). At complexes on St. Paul Island, interannual variation was primarily driven by differences in the dependence on juvenile pollock, other fish (primarily Pacific herring), and mature pollock. At St. George Island, interannual variation was largely driven by the presence of mature pollock in the diet in some years. There was overlap in all prey species consumed across rookery complexes, however, fur seals from St. George had much weaker interactions with juvenile pollock and other fish species, whereas fur seals from St. Paul

Island had much weaker interactions with squid species (Figure 2.4). Mature pollock was the one prey item that fur seals had moderately strong interactions with at all complexes.

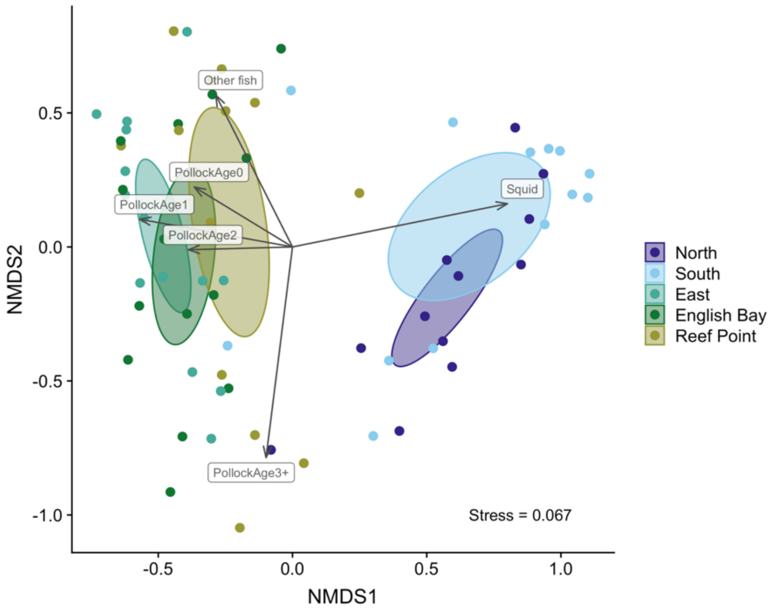

Figure 2.3. Non-metric multidimensional scaling results of the first two dimensions (of three) based on Bray-Curtis dissimilarities. Ellipses correspond to 95% CI based on standard errors. Arrows represent species correlations with each axis, with the length of each arrow corresponding to stronger correlations. Prey groups have been collapsed into broader categories encompassing squid and fish other than pollock, whereas pollock have been separated into four different age groups based on fork length.

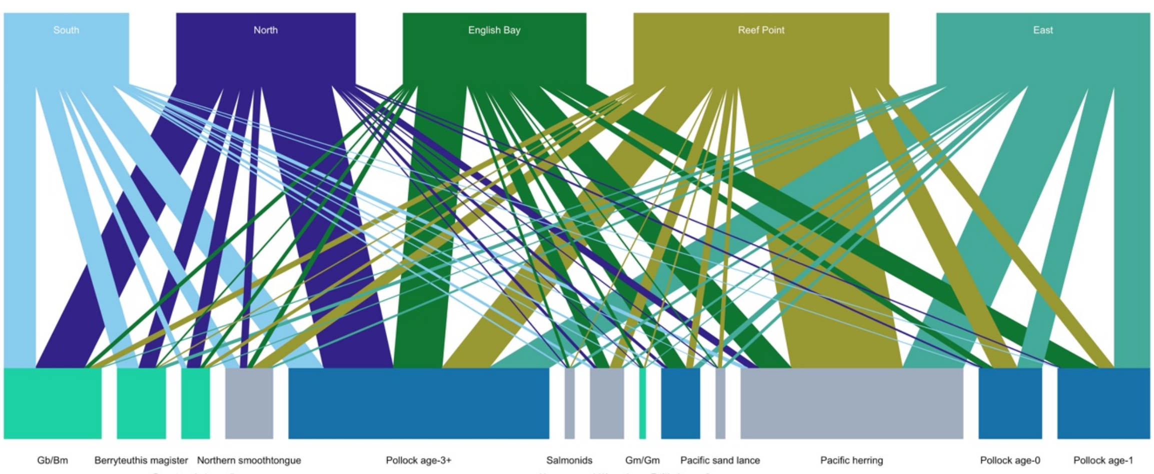

Figure 2.4. Visual depiction of food web interactions between fur seals at each rookery and their primary prey species. Prey species are colored based on assignment to one of three categories: squid (green), pollock (blue), or other fish (gray). Pollock were separated into four different age groups based on fork length. The importance of each prey species to the diet was

based on energy composition estimates averaged across all years at each rookery (n = 12 - 14 years). The thickness of each line represents the strength of the interaction.

The multiple regression analysis indicated that predictor variables only had predictive power at two of the five complexes, East (St. Paul) and North (St. George). For these complexes, important predictor variables were CPUE of non-pollock prey (primarily Pacific herring), the biomass of pollock < 30 cm, and PC1 (only North). Model fits were similar at both complexes ($r^2_{East} = 0.54$, $r^2_{North} = 0.50$). In general, the models appeared better at predicting consumption of mature pollock than juvenile pollock (Figure 2.5). For example, the diet data indicated that fur seals at North consumed very little juvenile pollock yet the model predicted high consumption of juvenile pollock in three years (Figure 2.5D). The reduced predictive power for juvenile pollock may be due to the fact that all fish data came from bottom trawl surveys, which underrepresents smaller mid-water prey species, such as juvenile pollock and squid. The poor predictive power at the other complexes may be due to this or other issues, such as having a smaller number of years with adequate sample sizes or lack of key environmental variables across all years (e.g. eddy variables were only available from 1993 onwards).

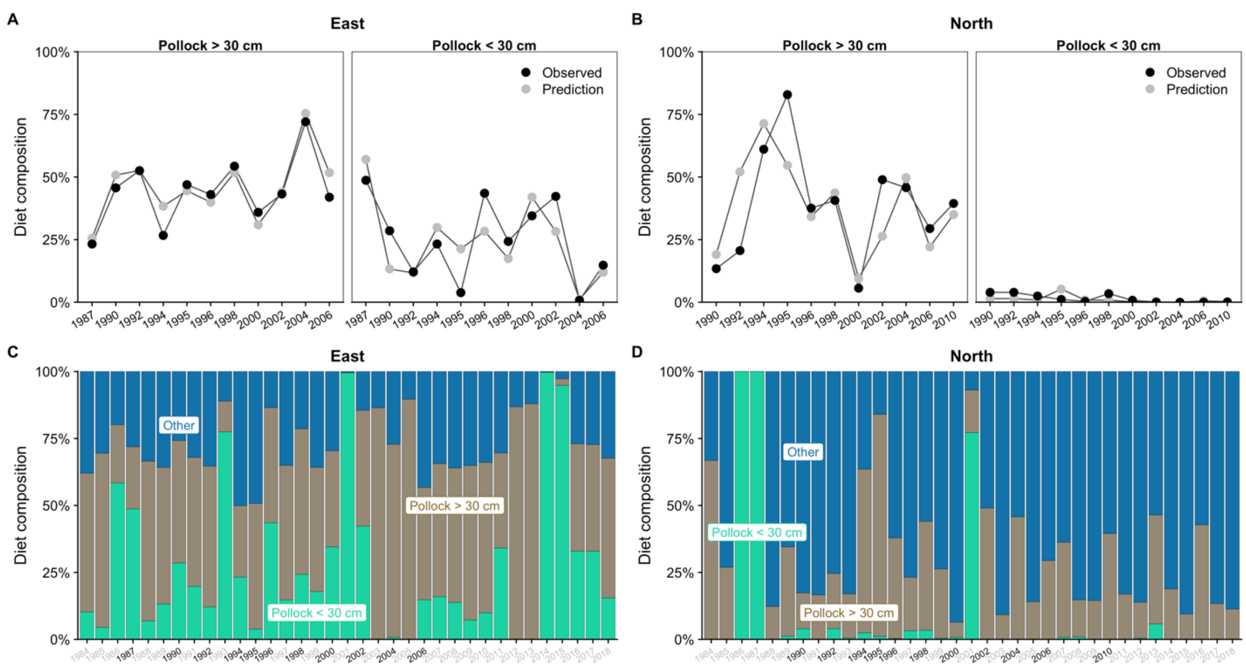

Figure 2.5. Comparisons between model predictions of fur seal diet composition of juvenile and mature pollock for St. Paul East (A) and St. George North (B), and predictions of diet composition between 1984 and 2018 (C and D). In C and D, predictions are provided for years without diet estimates with sufficient sample sizes.

The results from this objective highlight the continued need to collect and analyze fur seal scat and spew samples, as well as a need to refine explanatory variables to better capture the variables that are biologically relevant to fur seals. The output generated from this objective will be combined with energy estimates from a bioenergetic model and used to explicitly incorporate fur seal predation on pollock into the CEATTLE model. This is relevant to an ongoing project funded by the Lenfest Ocean Program and a recently funded COCA proposal. The inability to predict pollock diet composition at three rookery complexes remains to be addressed before fur seals can be incorporated into the CEATTLE model. One area we are pursuing is integrating the biennial mid-water pollock assessment, which would provide a more comprehensive view of the fur seals available prey field. The addition of the mid-water prey field could improve our fur seal diet prediction models, thus improving estimates of pollock mortality due to fur seal predation.