# Supplemental material describing the data for the model

All excel files an r-scripts are available on the github site at <https://github.com/bchasco/COAST_WIDE>. The model can be run using the buildModel.r wrapper. For each section we describe how the data were compiled, the assumptions that were made, specific files where the data are located, the Excel files related to summaries of the data or data interpolations, and r-scripts that are used to read in the files and build the model. In an attempt to maintain a clean version of the data without any equations, and in an easily readable format, we placed summary tables in a file labeled “appendixTables.xlxs”.

Lastly, we constructed a simple bioenergetics model in Excel model (“realityCheck.xlsx”) to assist readers and reviewers to understand how the parameters of the model affect the consumption of Chinook salmon. This Excel model doesn’t have the temporal or spatial components. It is meant to show how each predator’s abundance, mass, residence time in an area, diet fraction and prey size affect the number and biomass of Chinook salmon consumed.

# Predator abundance

The variable describes the predator abundance (see Methods section for equations). The summary of the predator abundances can be found in “Table\_PredatorAbundance” worksheet in the file appendixTables.xls. The predator abundance time series with model for estimating missing values can be found in predatorAbundanceSources.xlxs file: this file contains data from tables or figures in literature that were used to generate the complete estimates of abundance for all years with and without surveys. The data that are read into the model are found in the predAnnualTotals.csv files. This csv data file is read into the model using the create\_Nphy.r R wrapper script.

## Killer whales

The annual estimates of killer whale abundances are based on mark-recapture data. The southern resident killer whales (SRKW) in the Salish Sea have perfect detection probability, while the northern resident killer whales (NRKW) along the west coast Vancouver Island/British Columbia coast, southeast Alaska residents (SEAK) in the southeast Alaska area, and the western Alaska residents in the western Alaska area all have imperfect detection in their surveys. For our analysis the individual pods, or family groups, in each population include the following: J, K, and L pods; SRKW (Center for Whale Research 2016), +A102, -A11, -A30, -A24, -AC6, -G29, and -I11 pods; NRKW (Olesiuk et al. 2005), AF, and AG pods; SEAK (Allen and Angliss 2013), and AD, AI, AJ, AK, and AN pods; GOA (Allen and Angliss 2013, Matkin et al. 2014).

## Harbor seals

Harbor seal estimates are derived from time-series of haul-out data. In most cases these time-series have missing years. To interpolate those missing data, we use the MARSS package in R for time-series analysis. The abundance estimates for central California (Carretta et al. 2015, Codde and Allen 2015) are based on the San Francisco Bay and Point Reyes populations. The northern California population of harbor seals is based on the total California population estimate (Carretta et al. 2015) minus the central California estimate.

Columbia River harbor seal estimates are based on annual counts at the mouth of the river. These were digitized from a slide by Robin Brown from ODFW, in lieu of recent comparable estimates. .

The Oregon and outer Washington coast both have individual time-series of abundance based on the report by Carretta et al. (2015).

The Salish Sea estimate is a combination of federal (Carretta et al. 2015), state (Jeffries et al. 2003), and Canadian assessments (Canadian Science Advisory Secretariat 2010). These report include haul-out surveys which must be expanded by a factor of 1.52 to account for seals in the water.

West coast Vancouver Island, coastal British Columbia and Queen Charlotte Island populations are based on Canadian assessments (Canadian Science Advisory Secretariat 2010). These surveys are unique from the inland waters because they include both in-water and haul out surveys, so they do not need to be expanded by a correction factor of 1.52 for seals in the water; however, these survey are only a subset of the coast and survey indices needed to be expanded by a factor of 3 for un-surveyed portions of the coastline.

Time series of southeast Alaska and western Alaska populations of harbor seals are very sparse. We used a combination of the most recent Alaska stock assessment reports (Muto et al. 2016) and time-series of abundance from the literature (Boveng et al. 2003, Small et al. 2003, Jemison et al. 2006, Mathews and Pendleton 2006, Womble et al. 2010) to reconstruct estimate of harbor seal abundance. Complicating this effort is that not all areas were surveyed in every year, and the survey correction factors may not account for the same covariate between studies. Our estimates of Alaska harbor sea abundance allowed rough estimates of the number in western and southeastern Alaska. Based on the surveys we collected we had to: 1) extend the estimates of abundance beyond the margins of the surveys (i.e., pre-1992 and post-2003), 2) scale the regional estimates of abundance to total estimates of abundance, and 3) partition estimates of abundance into western and southeast Alaska areas.

## California sea lion

California sea lion populations are present in model areas 1 to 5 - central California north through the Salish Sea. The abundance estimates for California sea lions are based on pup count surveys conducted by state and federal agencies, and using an expansion factor for pup to adults (Angliss and Allen 2015). The largest concentration of California sea lions is in central California at the major breeding colonies in the Channel Islands and Año Nuevo, California (Carretta et al. 2015); this is the only time-series of any length for California sea lions and these sea lions are considered to be part of central California population.

Only California sea lions ages 6 and older are likely to prey on Chinook salmon (Jeff Laake, pers. comm. NOAA). However, the time-series of abundance for California sea lions is based on pup counts expansions. Multiplying this by the fraction of the population that is age 6 and older ( Jeff Laake, pers. comm NOAA) yielded the number of male and female age 6+ California sea lions. We assume that all age 6+ females remain in Central California. The number of age 6+ males in Central California is assumed equal to the total number of age 6+ males minus the abundance in the other regions as detailed below.

Based on a single technical report (National Marine Fisheries Service (NMFS) 1997), we estimated that the California sea lion population on the outer coast of Washington is 500 individuals, while the Oregon coast population is 4,800 individuals. We have no time series information on these populations and so there is no change in abundance for these areas during the duration of the study.

Columbia River sea lion estimates are based on a time series of peak counts from a presentation by Robin Brown (pers. comm., Oregon Dept. Fish and Wildlife, 7/29/2015). These peak counts for the Columbia River are only from 2004 to 2015; however, we know that California sea lion were in the Willamette River starting in the early 1990s (Wright et al. 2015). We fit a simple exponential growth model to the peak observation between 2004 and 2015, and then back calculated the number of California sea lions present in the Columbia River between 1990 and 2003 (see “CSL\_ColumbiaRiver” worksheet in the predatorAbundanceSources.xlsx file).

The abundance of California sea lions in the inland waters of the Salish Sea was based on published surveys and estimates (Bigg 1985, Edgell and Demarchi 2012, Jeffries et al. 2014). We chose to fit a logistic model to the time series of observations in Edgell and Demarchi (2012) based on the single haul-out location at Race Rocks. While the earlier time series of Biggs (1985) includes several other haul-out sites in the Strait of Georgia, we chose not to include these observations in our estimates because they do not overlap with later surveys. This could lead to a negative bias in our population estimate from Edgell and Demarchi. Since the Race Rock survey is for hauled-out sea lions, we use an expansion factor of two to account for sea lion that were in the water during the survey.

We used the time-series of abundance from Bigg (1985) to estimate the number of California sea lions along the west coast Vancouver Island/British Columbia area. Again, we fit a logistic model to the available survey data to estimate years with missing data. We did not multiply this estimate by an expansion factor because this survey included both haul-out and in-water (i.e. rafting) observations.

Recently small numbers of California sea lions were observed in Alaskan waters, but we have chosen not to model these based on the short time-series and limited observations (Maniscalco et al. 2004).

## Steller sea lions

While NOAA has produced time series of abundance for the Steller sea lion populations along the eastern Pacific, the spatial resolution of these estimates does not match our model spatial areas. We therefore disaggregated many of the NOAA abundance estimates for California, Washington, Oregon, British Columbia, and southeast Alaska. As described below in more detail, we had to disaggregate the California population into central and northern California, and we estimated a time-series of abundance for Salish Sea inland waters. We also derived estimates of Steller sea lion abundance specifically for the Columbia River and Gulf of Alaska.

We divided Steller sea lion abundance in California into northern and central California regions, using analyses by Pitcher et al. (2007) and Angliss and Allen (2015) . Based on the figures in (Pitcher et al. 2007) the ratio between the numbers at Año Nuevo (central California) and the numbers at St. George reef (northern California) has steadily decreased. We digitized the plot in (Pitcher et al. 2007) and fit exponential curves to the haul out data for each area. We then used the curves to estimate the ratio of central and northern California Steller sea lion populations over time (see the “SSLinterpolated” worksheet in predatorAbundanceSources.xlsx for ratios).

The Gulf of Alaska population estimates were based on survey estimates from Sease et al. (2001) and Fritz et al. (2008), and unpublished data by Trites and Donnelly (2003). We placed the analysis of the Gulf of Alaska Steller sea lion numbers in a separate worksheet titled, “SSL\_EGULF” in the predatorAbundanceSources.xlsx file.

The population of Salish Sea Steller sea lions are mostly likely transient males that migrate from coastal British Columbia and the Washington Coast to inland waters during the fall, winter and spring months (Bigg 1985, Jeffries et al. 2014). Because their population numbers are low relative to other areas, it was easier from a modeling perspective to treat these individuals as if they were a separate Salish Sea population; within the model, during the summer months when they are not present they are distributed evenly along the Washington Coast and outer British Columbia coast. We found three surveys of Steller sea lion abundance in the Salish Sea: Bigg (1985), Edgell and Demarchi (2012), and Jeffries et al. (2014). During the 1970s Bigg observed approximately 35-330 Stellers sea lions in British Columbia inland waters, Jefferies observed peaks counts of ~350 in Washington State inland waters, and Edgel and Demarchi observed haul-outs of 680 individuals at Race Rocks in the Strait of Juan de Fuca. Similar to the California sea lion estimates for the Salish Sea, we fit a logistic model to the Edgell and Demarchi time-series because it was the most complete of the three surveys, with the understanding that using just Race Rocks surveys probably represents an underestimate of Steller Sea lion abundance. We then multiplied the haul-out estimates by a correction factor of two to account for sea lions in the water.

We have no time-series of abundance estimates for the Columbia River. A table in Wiles (2015) describing the range of maximum numbers in the Columbia River between 1976 and 2014 is our best source of information. Based on the range given in Wiles (2015), we simply assumed that Steller sea lion have a time-series of abundance that is equal to California sea lions described by Brown.

# Predator age and sex structure

This section describes the variables related to predator age structure, , and predator sex ratio, – specifically, the percentage of females at each age. A brief summary of the age and sex ratios of the predators is contained in the worksheets “Table\_PredatorAgeRatios” and “Table\_PredatorFemaleRatios” in the appendixTable.xlsx file. The raw data for each species can be found in predatorAgeRatios.csv and predatorFemaleRatio.csv. They are read into the model with the create\_Nphyis.r wrapper.

The sex and age distributions of the southern and northern resident killer whales in the Salish Sea (Ward et al. 2009, Center for Whale Research 2016) and west coast Vancouver Island/British Columbia (Ward et al. 2016) are based on small populations with a high percentage of marked and recapture individuals. The sex and age distributions of these populations are known with very little error. Southeast and western Alaska residents are based on stage-based estimates from (Matkin et al. 2014). Without additional information on survivorship, we evenly distributed that fraction of the population in each stage across all ages within a stage.

The sex ratios for seal and sea lions are known with less precision. We used sex and age-specific survivals for harbor seal (Bigg 1969, Pitcher and Calkins 1979; Table 18, Hastings et al. 2012), California sea lion (Hernández-Camacho et al. 2008), and Steller sea lion (Winship et al. 2002), and fecundities (harbor seals (Härkönen and Heide-Jørgensen 1990), California sea lions (Hernández-Camacho et al. 2008, French et al. 2011), and Steller sea lions (York 1994)) to estimate the stable age distributions of male and female pinnipeds (see the excel file PinnipedStableAgeDistributions.xlsx for projections of the stable age distribution).

Based on input from Jeff Laake at the NOAA Marine Mammal Laboratory (*pers. comm ,* 12/19/2016 ), only California sea lions age 6 and older in any of the areas are likely to be preying on Chinook salmon. Therefore, after determining the stable age distribution for California sea lions, we normalized the ratios to include only those ages six and older.

For some predators like California and Steller sea lion in the Columbia River and the Salish Sea, and California sea lions along the outer coasts of Washington and Oregon, the populations are dominated by sub-adult and adult males. In those instance, the ratio of females in those populations were set to zero.

# Predator mass

For a summary of the predator weight-at-age see the worksheet “Table\_PredatorWeightAtAge” in the appendixTable.xlsx file. The variable in the model is . The data for the model are in predatorWeightAtAge.csv and the data are read into the model with the create\_Mphis.r wrapper.

The predator mass is based on published results in the literature. Killer whale mass-at-age was taken directly from the appendix in (Noren 2011). California and Steller sea lion mass-at-age is based on the models in (Winship et al. 2006) and (Winship et al. 2001), respectively. We were unable to find a mass-at-age relationship for Pacific harbor seals. There is a relationship for Atlantic harbor seals (Boulva et al. 1979) but we were uncertain if these seals were representative of the seals in the Pacific. Instead we used data from Figure 8 on page 269 of (Pitcher and Calkins 1979) and then fit a Gompertz relationship to the median estimates in the figure.

# Bioenergetic multipliers and digestive efficiency estimates

The variables in the model for the Kleiber multiplier and digestive efficiency are and , respectively. The Kleiber multipliers for killer whales (Noren 2011), harbor seals (Boyd 2002, Howard et al. 2013), California sea lions (Weise and Harvey 2008), and Steller sea lions (Winship et al. 2002) are based on published literature values. Units are inconsistent in this literature: watts, joules or calories are reported. For consistency, we describe all of the Kleiber multipliers in units of (kcal/kg). The data input file for the R model is kleiberAlpha.csv. The efficiency inputs are in the wrapper create\_EPphis.r. The details of the Kleiber multiplies and digestive efficiencies of each predator are described below.

## Killer whales

The killer whale energetic requirements are based on Noren (2011). Noren (2011) produced estimates in kcal/kg so there is no transformation of units. The multiplier is straight forward: it is based on the average field metabolic rate (FMR) based on equations 1 and 2 in Noren (2011). The digestive efficiency of killer whales is estimated to be 0.847 from (Williams et al. 2004).

## Harbor seals

We apply the Howard et al. (2013) bioenergetics model for harbor seals, which is based on Boyd (2002). In the Howard paper there are three activities, each with a separate activity multiplier: rest, diving, and surface in a ratio of approximately (20/40/40). Based on this ratio of activities , and transforming from original units of watts to calories, the average activity multiplier for harbor seals is 103 kcal/day. Based on Howard et al. the combination of digestive and heat loss results in an efficiency of 0.825.

## California sea lions

The field metabolic rate multiplier for California sea lions was 305 for at-sea, and 122 on-shore, with the time at-sea and on-shore being about 50/50 for an average FMR of 214 (Weise and Harvey 2008). This estimate is also in kcal/kg so there is no converting from joules. However, this estimate does not account for digestive efficiency which we set equal to 0.875 based on the value for Steller sea lions in (Winship et al. 2002).

## Steller sea lions

The estimate of energetic demands for Steller sea lion is based on (Winship et al. 2002). The Winship estimate is in kJ/kg and varies by sex and age. The basal metabolic rate is 293. The metabolic multipliers for on-shore and off-shore activities are 1.2 and 4.0, and the percentage of the time on land is about 70%, versus 30% for off-shore. This gives a rough estimate of 230 for (i.e., (1.2\*0.3+4\*0.7)\*293 / 4.184(J/cal)). We additionally account for digestive efficiency, which is 0.875 (Winship et al. 2002).

# Fraction of the energy derived from Chinook salmon

The fraction of Chinook salmon in the predator diets is described by in the methods sections. For a summary of the data see “Table\_predatorDietFraction” in the appendixTables.xlsx file. The raw data are available in the predatorDietFraction.csv file. The data are read into the model with the create\_FECpjt.r wrapper. There are many assumptions to diet fraction estimates, which motivated the broad CVs for diets within our sensitivity analysis.

Killer whales diet information is known with more precision than for pinnipeds, since killer whale diet information is based on direct observation, or the genetic analysis of scat. For pinnipeds, the fraction of Chinook salmon in the diet is more uncertain because: 1) most diet data is based on frequency of occurrence data (FO) where the fractions for different prey taxa do not sum to one, and 2) often the FO data are an aggregation of all salmon rather than just Chinook salmon.

We used information from (Thomas et al. 2016) to transform Chinook salmon FO data into split-sample frequency of occurrence (SSFO) data based on paired observations in their analysis. SSFO calculates average prey occurrence as a fraction across all individual scat samples rather just a frequency of occurrence across scat samples; therefore, the prey fractions sum to one. Thomas et al. (2016) found different FO to SSFO correction factors for juvenile (ocean age 0) and adult (ocean age 1+): for juveniles, the correction factor is 0.24, meaning that the SSFO is about one quarter of the FO estimate. The correction factor for adult salmon is 0.16.

The FO diet data were based primarily on as synthesis by Adams et al. (2016) which compiled over 300 diets studies for marine mammal predators in the eastern Pacific. Unfortunately, many of the salmon estimates are grouped at the genus level, and we needed estimates of Chinook salmon in the diets. To transform the estimates of aggregate salmon to Chinook salmon, we weighted the FO estimate by the average ratio of Chinook salmon in the sport and recreation catch relative to all salmon in the sport and recreational catch, and assumed that predators have the same selectivity for adult salmon as the fishermen. The ratios of Chinook salmon relative to all salmon are: central California 0.95; Northern California and coastal Oregon, 0.90 (see <http://odfw.forestry.oregonstate.edu/spawn/pdf%20files/coho/CoastalCohoESUSpawnHarvestSummary.pdf> and Coho technical committee report); Columbia River, 0.58 (http://www.critfc.org/fish-and-watersheds/columbia-river-fish-species/columbia-river-salmon/); outer Washington coast, 0.30 (see <http://wdfw.wa.gov/fishing/harvest/> and Chinook technical committee report). Salish Sea Chinook salmon fraction is highly variable because the odd/even year influence of pink salmon but we assume a ratio of 0.05 (Henderson and Graham 1998); BC coast, 0.04 (Henderson and Graham 1998); southeast Alaska, 0.0006 (see http://www.adfg.alaska.gov/index.cfm?adfg=commercialbyareasoutheast.salmon\_harvestbyspecies), and western Alaska; 0.0004 (http://www.adfg.alaska.gov/index.cfm?adfg=commercialbyareasoutheast.salmon\_harvestbyspecies). Based on these estimates of average Chinook salmon fraction in the catch, we multiplied any aggregate salmon FO estimates by these correction factors. We recognize that in many instance, the odd and even year fraction of Chinook salmon relative of other salmon species will vary dramatically as a function of the pink salmon returns.

Within our Columbia River region, we create average diet compositions that account for California and Steller sea lion individuals that appear to feed directly at the dam and specialize on salmon, versus individuals that feed on a broader set of prey in the lower Columbia River. We assume that ~7% of each sea lion population in the Columbia River model region feeds directly at the dam, and the other 93% feed in the lower river, based on reports for California Sea Lions [[1]](#footnote-1). The diets of the 7% of the California sea lions that feed directly at the Bonneville have a diet fraction of about 72% Chinook salmon (Adams et al. 2016), and this is based on direct observation, so no FO correction factor is needed. The diet fraction of 93% of California sea lions in the lower river is 18.1% FO aggregated across all salmon species (Adams et al. 2016). This translates into about 10.5% FO after accounting for the fact that Chinook salmon are typically 58% of the total returning salmon. The diet fraction of the Steller sea lion feeding directly at the base of Bonneville dam is 39.4% (Adams et al. 2016). In the lower river, Steller sea lion consumption of all salmon species is 25% FO (Adams et al.2016, based on a single study), equivalent to an FO of 14.5% for Chinook salmon.

# Predator age selectivity of Chinook salmon

The variable for selectivity in our model is . A summary of the selectivity data can be found in “Table\_AverageSELAcrossMonths” in the appendixTables.xlsx file. The selectivity data are found in predatorAgeSelectivity.csv, and the wrapper to read in and process the data is create\_SELpjta\_basedOnMaturationSchedule.r .

Because a gram of juvenile Chinook salmon is assumed to have the same caloric value as a gram of adult Chinook salmon, the biomass of Chinook consumed only depends on the fraction in the predator diet. The number of Chinook salmon that are consumed, however, depends on the size of the Chinook salmon consumed because, for instance, a four ocean adult is equal to ~1,400 juvenile smolts.

Killer whales do not eat juvenile smolts and the selectivity of different ages of adult Chinook salmon can be estimated from scale pattern analysis from predation events (Ford and Ellis 2006). Although the analysis by (Ford and Ellis 2006) focused on Salish sea killer whale diets, we apply this same age selectivity for the other three resident killer whale populations.

The size selectivities for the pinnipeds in our model are based on the synthesis by (Adams et al. 2016). The studies in this synthesis differentiate the size selectivity of pinnipeds based on hard parts in the scat, but they only define salmonid sizes as either juvenile or adult. We chose to distribute the fraction of adults proportionally across the age distribution of Chinook salmon returning to each area. A summary of the papers used to estimate the temporal and spatial diets fractions of the predators is provided below.

Table 1. Sources used to estimate the age selectivity for killer whales and harbor seals.

|  |  |  |
| --- | --- | --- |
| Area | Killer whale | Harbor seals |
| Central California |  | (Scordino 2010) found mostly consumption of adult salmon, we assume this to be **1:9** juvenile to adult. |
| Northern California/ Oregon |  | (Scordino 2010) found mostly consumption of adult salmon, we assume this to be **1:9** juvenile to adult. |
| Columbia River |  | (Scordino 2010) found seasonal differences in the **juvenile:adult** composition: Spring **1:2,** Summer **1:1 ,** Fall **0:1**. (Browne et al. 2002) suggest based on FO data of all skeletal remains that the juvenile:adult ratio was Spring **19:6**, Summer **5:4** , Fall **1:2**. Spring is March-May, Summer is June - Aug, Fall is Sept-Nov, Winter is December - Feb. Without additional information on the Winter diet, we assume no Chinook in the diets |
| Outer Coast Washington |  | Without detailed size composition of the harbor seal diets along the coast, we chose to use the same estimate as (Thomas et al. 2016) from the Salish Sea: Apri **1:2**, May **1:1** , June 3:1, July **1:1**, August **1:1**, Septemberl **1:15**. October **1:5**, November **0:1.** Since there is no information for Dec,Jan,Feb,Mar, we used Nov ratios for Dec and Jan, and Feb, and Apr ratios for March |
| Salish Sea | (Ford and Ellis 2006) and (Hanson et al. 2010) provide age specific estimates of killer whale consumption based on scales, **2% age one, 18% age two, 55% age three, and 25% age four** | (Thomas et al. 2016) found monthly differences in the **juvenile:adult** composition: Apri **1:2,** May **1:1 ,** June **3:1,** July **1:1,** August **1:1,** Septemberl **1:15.** October **1:5**, November **0:1**,. Since there is no information for Dec,Jan,Feb,Mar, we used Nov ratios for Dec and Jan, and Feb, and Apr ratios for March |
| Outer Vancouver Island / British Columbia | (Ford and Ellis 2006) and (Hanson et al. 2010) provide age specific estimates of killer whale consumption based on scales, **2% age one, 18% age two, 55% age three, and 25% age four** | Because there were no harbor seal size selectivity data for outer Vancouver Island or coastal BC, we chose to use the juvenile:adult ratios from (Herreman et al. 2009): **1:2** or **1:3**. |
| Southeast Alaska | (Ford and Ellis 2006) and (Hanson et al. 2010) provide age specific estimates of killer whale consumption based on scales, **2% age one, 18% age two, 55% age three, and 25% age four** | (Herreman et al. 2009) found that the ratio of juvenile:adult salmon (not Chinook) was **1:2** or **1:3**. |
| Western Alaska | (Ford and Ellis 2006) and (Hanson et al. 2010) provide age specific estimates of killer whale consumption based on scales, **2% age one, 18% age two, 55% age three, and 25% age four** | Because there were no harbor seal size selectivity data for western Alaska, we chose to use the juvenile:adult ratios from (Herreman et al. 2009): **1:2** or **1:3**. |

Table 2. Sources used to estimate the age selectivity for California and Steller sea lions.

|  |  |  |  |
| --- | --- | --- | --- |
| Area | California sea lion | | Steller sea lion |
| Central California | (Scordino 2010) found very little information on the size of the salmon in the CSL diets, but suggests that most of the salmon are adults stolen from nets, **100% adult.** | In the absence of size selectivity for Central California, we chose to use (Scordino 2010) which indicates that Stellers are only eating **100% adults.** | |
| Northern California/ Oregon | (Scordino 2010) found very little information on the size of the salmon in the CSL diets, but suggests that most of the salmon are adults stolen from nets, **100% adult.** | (Scordino 2010) indicate that Stellers are only eating **100% adults.** | |
| Columbia River | (Scordino 2010) and (Stansell et al. 2010) suggest that the majority of the Chinook consumption is from adults, **100% adult.** | Based on (Stansell et al. 2010), there is no indication that Stellars were eating anything but **100% adults.** | |
| Outer Coast Washington | (Scordino et al. 2014) found time-varying patterns in **juvenile:adult** ratios for salmon consumption: **1:1** Spring, **1:4** Summer, and **1:4** Fall. Without additional information on the Winter diet, we used the Spring fractions for January and February, and the Fall fractions for December | (Scordino et al. 2014) found seasonal differences in the size composition of the juvneile:adult ratio: **6:1** Spring, **1:1** Summer, **4:3** Fall, **26:1** Winter. | |
| Salish Sea | There are no size selectivity studies for the Salish Sea. There are similarities between CSL estimates by (Scordino et al. 2014) and HS estimates by (Thomas et al. 2016). We chose to use the Outer coast estimates from (Scordino et al. 2014): **1:1** Spring, **1:4** Summer, and **1:4** Fall. | There are no size selectivity studies for the Salish Sea. (Scordino et al. 2014) found seasonal differences in the size composition of the juvneile:adult ratio: **6:1** Spring, **1:1** Summer, **4:3** Fall, **26:1** Winter. | |
| Outer Vancouver Island / British Columbia | We found no size selectivity estimates for the Outer Vancouver Island or British Columbia. Given the similarities between harbor seal and California sea lion diets in the Salish Sea and along the outer coast of Washington, respectively. We chose to use the size selectivity of the harbor seals in from Southeast Alaska based on the (Herreman et al. 2009) study: **1:2** or **1:3**, juvenile to adult. | There are no size selectivity studies for the outer Vancouver Island and coastal BC. (Tollit et al. 2015) and (Sigler et al. 2009) estimated the fork length of the salmon in the diets to be **32.5** cm and **31+-12**cm . That is approximately the size of age 1 fish. Without any other information we assumed that all of these were ocean **age 1**. | |
| Southeast Alaska |  | There are no size selectivity studies for the outer Vancouver Island and coastal BC. (Tollit et al. 2015) and (Sigler et al. 2009) estimated the fork length of the salmon in the diets to be **32.5**cm and **31+-12**cm . That is approximately the size of age 1 fish. Without any other information we assumed that all of these were **age 1**. | |
| Western Alaska |  | Sinclair and Zeppelin (2002) found mostly adult size fishes, although salmonids comprised less than 5% FO. We assumed that this meant there were no smolts in the diets and only **100% adult**. | |

# Predator temporal and spatial distributions

The variable in the model that describes the predator distribution is . Data for the model is determined by results found in the literature, or by expert opinion when data are lacking. Each of the predators in our model is assumed to originate from a home area. Throughout the course of the year the different predator population may disperse based on their sex – male California and Steller sea lions are more mobile. That raw data that are input into the model are found in the file predatorTemporalSpatialDistribution.csv, and the wrapper that reads in and processes the data is create\_PHIphjts.r. For a summary of the data see the worksheet “Table\_temporalSpatialPredator” in the appendixTables.xlsx spreadsheet.

## Killer whales

Southern resident killer whales occupy Salish Sea waters from May to early November. During that period they are not in Salish Sea waters 100% of the time – even during their peak occupancy in summer months they only occupy inland waters 80% of the time (Hauser et al. 2007, National Marine Fisheries Service 2008). During the summer months we assume that 20% of SRKW are not present in Salish Sea waters, and instead are evenly distributed among the areas from central California to the west coast of Vancouver Island. There are three pods of killer whales in the Salish Sea: J, K, and L. During the winter months J-pod, which represents about 30% of the population, spends about 25% of its time in Salish Sea waters. The remainder of its time is spent evenly between Central California, Northern California and Oregon, and the outer coast of Washington. The K and L pods are assumed to spend their time evenly between Central California, Northern California and Oregon, and the outer coast of Washington, and no time in Salish Sea waters. This means that about 7.5% of the population occupies the waters of the Salish during the fall and winter months.

Northern residents killer whales occupy the waters of west coast Vancouver Island and the British Columbia outer coast 100% of the time (Barrett-Lennard et al. 1995, Nichol and Shackleton 1996). During the summer months the northern resident are known to feed in Johnstone Strait at the northern end of Vancouver Island but we do not consider this area to be part of the Salish Sea.

The killer whales in the Gulf Of Alaska (Prince William Sound, Cook Inlet, Kenai, and Kodiak Island) appear more mobile than the other resident populations (Matkin et al. 1999). Whales from Prince William Sound can be observed in southeast Alaska and off of Kodiak Island (Matkin et al. 1999), and whales from southeast Alaska are known to occupy waters of western Alaska. To reflect their mobility of the southeast resident killer whales we assume they spent 50% of their time in western waters and 50% in southeastern waters. For western residents we simply assume they spend 100% of their time in Gulf of Alaska waters.

## Harbor seal

Harbor seals are assumed to be year-round residents in their area of origin, with no exchange between adjacent areas (Suryan and Harvey 1998). The one exception is for harbor seals in the Columbia River. We assume these seals migrate to the outer coast during the breeding season – half go to the Washington coast and the other half go to the Oregon coast. Some evidence suggests that harbor seals may migrate more than previously expected. A recent study (Peterson et al. 2012) demonstrated two of the 20 seals fitted with satellite tags in Salish Sea waters migrated briefly to the outer coast of Washington during the spring months. However, for the purposes of this study we assume they remain year round residents of their home area.

## California sea lion

We assume the population of female California sea lions in central California are year-round populations. From the model perspective it is easier to assume the populations of male California sea lions are resident in the Salish Sea (Bigg 1985, Jeffries et al. 2014), Columbia River (Robin Brown pers comm.), and coastal populations of Oregon and Washington, and they migrate to the central California area during their breeding periods in May and June. In addition to the seasonal movements to the breeding colonies in California, there is a decline in the abundance of sea lions during the winter in the Salish Sea and Columbia Rivers. During this time we assume that the sea lion move to the bays and estuaries along the outer coast of Washington and Oregon.

## Steller sea lions

Similar to the California sea lion populations, it is easier to assume the populations of Steller sea lions in the Salish Sea (Bigg 1985, Jeffries et al. 2014) and Columbia River (Stansell et al. 2010, Robin Brown pers comm.) are residents that migrate to adjacent areas during periods of absence. However, since we do not know exactly where they migrate to when they are absent (Bigg 1985) we have chosen to assume that they move to the bays and estuaries on the outer coasts of Washington, Oregon, and Vancouver Island.

# Chinook salmon production

The variable that describes the recruitment of Chinook salmon to the areas where predation occurs is . There are two files containing the raw data related to smolt production: Smolt\_AllData.csv which is the hatchery production, and WildProduction.csv which are the estimates wild production based on the escapement data. The data are read in with the wrapper create\_Rhroy.r. A summary of the wild and hatchery production is in the worksheet “Table\_SmoltProduction” in the appendixTables.csv file.

There are two sources of Chinook salmon production – hatchery and natural origin fish. Estimates of hatchery production were determined using the RMIS database (RMIS 2012). There are a number of ways to generate the abundance of outmigrating smolts. We used the “Adclipped Releases” database (see Figure 1, a screen of the options we selected) and selected only Chinook salmon releases. Although the database are labeled Adclipped releases, it includes an estimate of both adclipped and unmarked releases. Using the “release\_location\_rmis\_region” field in the RMIS database we were able to map the release data to the areas in our model (Table 3).

There is no database for wild smolt production. To estimate the annual smolt production we compiled escapement data for natural spawners in the tributaries along the west coast based on reports from Department of Fisheries and Oceans (2014), Pacific Fishery Management Council (2016), PACIFIC SALMON COMMISSION JOINT SALMON (2016) (Table 4). With the exception of the Canadian stocks, most of the escapement estimates are available as downloadable Excel files from management websites. In the case of the Canadian stocks we had to digitize the escapement figures based on their presentation of post season results (DFO 1999, Heard et al. 2007).

There are very few experiments to estimate the number of natural origin juvenile produced. To estimate natural origin smolts we multiply the estimated escapement by 0.5 to estimate the number of female spawners, and multiply the number of female spawners by the average number of juveniles-per-female. The estimated average number of juveniles-per-females was 200 (Table 5).

Figure 1. Screen shot of the RMIS database page. Select the adclipped releases on the left-hand side, and then enter 1 for species type.



Table 3. Lookup table for the relationship between the area names in our model and the regional tag code identifiers for hatchery released Chinook salmon in the RMIS database.

|  |  |  |
| --- | --- | --- |
| Area ID | Area name | release\_location\_rmis\_region |
| 1 | Central California | CAGN, CECA, SAFA, SJOA |
| 2 | Northern California/Oregon | KLTR, NOCA, NOOR, ORGN, SOOR |
| 3 | Columbia River | CECR, CRGN, LOCR, SNAK, UPCR |
| 4 | Outer Washington Coast | GRAY, NWC, WAGN, WILP |
| 5 | Salish Sea | FRTH, GST, HOOD, JNST, JUAN, MPS, NOWA, NPS, QCI, SKAG, SPS |
| 6 | West Coast Vancouver Island/Coastal British Columbia | COBC, NASK, WCVI |
| 7 | Southeast Alaska | ALSR, CHIL, SEAK, STUN, TAWH, TRAN |
| 8 | Western Alaska | WEAK |

Table 4. Tributaries in each area and estimate average escapement based on Chinook Technical Committee reports, Pacific Salmon Commission Appendix A report, and presentations by Department of Fisheries and Oceans in Canada. In some instances reports group escapement estimates (e.g., above Bonneville, west coast Vancouver Island index streams, etc.).

|  |  |  |  |
| --- | --- | --- | --- |
| Area ID | Area name | Watersheds | Average escapement |
| 1 | Central California | San Joaquin, Sacramento | 151,431 |
| 2 | Northern California/Oregon | Klamath/Trinity, Oregon North Coast, Oregon South Coast, Shasta Area, Rogue, Rogue/Umpqua | 173,642 |
| 3 | Columbia River | Above Bonneville, below Bonneville, Mid-Columbia Brights, Up-River Brights | 323,297 |
| 4 | Outer Washington Coast | Grays Harbor, Hoh, Queets, Quilyutte, Quinalt, Willapa Bay | 31,045 |
| 5 | Salish Sea | Fraser, Hood Canal, Puget Sound, Skagit, Stillaquamish/Snohonmish | 91,022 |
| 6 | West Coast Vancouver Island/Coastal British Columbia | West coast Vancouver Island aggregate, Nass, Skeena | 76,215 |
| 7 | Southeast Alaska | Copper, Stikine, Skeena | 93,982 |
| 8 | Western Alaska | Chignik, Karluk, Kenai, Susitna | 75,612 |
| Total |  |  | 1,016,248 |

Table 5. Natural juvenile production estimates based on a review of the available literature.

|  |  |  |  |
| --- | --- | --- | --- |
| Source | Tributary | Run type | Estimate and page number |
| (Kiefer et al. 2002) | Snake River | Spring/Summer | 243 |
| (Zimmerman et al. 2015) | Skagit River | Spring, summer/fall | 750, page 8 |
| (McPherson et al. 2003) | Taku River | Spring/Summer | 90, page 28 |
| (Seiler et al. 2004) | Green River |  | 90, page 2-16 |
| (Seiler et al. 2004) | Chiwawa | Sping | 233, page 3-17 yearling only |
| (Carmichael et al. n.d.) | Upper Grande Ronde | Spring | 80, page 15 |
| (Kinsel et al. 2008) | Skagit River | Spring, summer/fall | 218, page 26 |
| (Kiyohara and Volkhardt 2008) | Bear creek | Fall ? | 303, page 43 |
| (Kiyohara and Volkhardt 2008) | Cedar | Fall ? | 703, page 28 |
| Lamperth et al. 2013 | Coweeman | Fall | 560 |
| (Seiler et al. 2005) | Cedar | Fall ? | 479, page 38 |
| (Seiler et al. 2005) | Bear creek | Fall ? | 95, page 53 |

# Chinook energy content

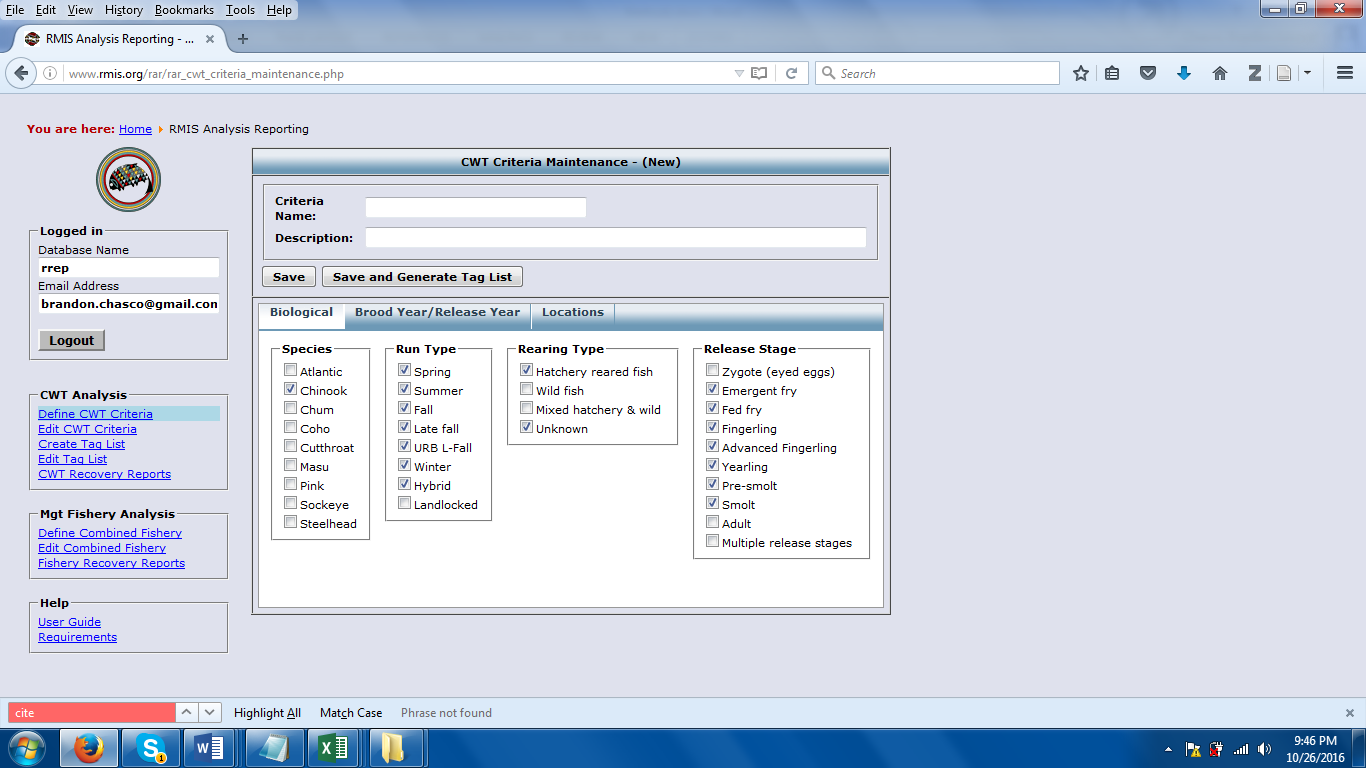
The variable related to Chinook salmon energy in our model is . The energy of Chinook salmon was estimated as a function of its length, and the data on Chinook length were derived from release data in the RMIS database for coded-wire-tagged (CWT) fish. Our assumption was that wild and hatchery fish are about the same size, and the average size of release fish by area and run type reflects the mixture of sub-yearling and yearling fish in the populations. The raw length data for the model are in Smolt\_AllData.csv for the juveniles, and ChinookLengthAtAge.csv for the adults. The wrappers to create the length-at-age arrays are create\_SMTLhryt.r and create\_CLAmrota.r. A summary of the length at data is available in the worksheet “Table\_ChinookLengthAtAge” in the appendixTable.xlsx file. Lastly, the wrapper to transform the length-at-age of Chinook salmon into energy-at-age of Chinook salmon is in create\_EChromta.r.

We used the energy model developed by (O'Neill et al. 2014) to estimate the kcal of Chinook salmon energy as a function of Chinook salmon length. Smolt length is based on average length of smolt releases from the RMIS database. We used a separate database than the one that was used to estimate the hatchery total production. Figure 2 shows a screenshot of how we queried the data. We used the same regional codes in Table 3 to map the hatchery release locations to the areas in our model. Our estimates of smolt length did not vary across years, but they did vary by area, run type, and across months (Table 6). In many cases there may have been no recorded smolt lengths for a particular area and run. When that occurred we took the average of the smolts lengths from the adjacent areas by run type, and if there were no observations for a run in the adjacent areas we took that average across all observed runs in the adjacent areas.

Based on work by Teel et al. (2015) and Weitkamp et al. (2015) we expect the juvenile Chinook salmon to stay in the coastal areas for more than one model time-step. Rather than model the residence of juvenile Chinook salmon in each area, we assumed that the size of the juveniles was equal to the release size of the juvenile, plus 40 days of growth – 10 days for the estimated migration time between the release site in the rivers, or rearing location for natural stocks, and an additional 30 days for the average residence time in each area. Based on work by Weitkamp et al. (2015) we used an average of 1.0 mm/day in growth for all run types.

Monthly estimates of adult length-at-age were based on model estimates from the FRAM model (Clemons et al. 2006; Table 6). These estimates are for specific river systems in each area. To get an aggregate estimate adult size within an area, we simply averaged across all rivers within an area – ignoring any weighting based on the relative abundance of fish returning for the different rivers. The FRAM model did not have estimates of the length of ocean age 5 Chinook salmon, so we projected the von Bertalanffy model forward based on average growth parameters across all rivers (Linf equals 1146, K equals 0.0305, and t0 equals -2.79) and estimated the average length of an ocean age five individual. Note the parameters of the FRAM model are for a monthly time step, so the age of five ocean fish is 72 months, not 5 years.

Figure 2. Screen shot of the RMIS website and the tabs that were selected to produce the data for estimating the smolt lengths and migration timing.



# Chinook salmon distribution

The variable describes the spatial distribution of the Chinook salmon in our model. A summary of the distribution can be found in the worksheet “Table\_ChinookTempSpatialDist” in the appendixTables.xlsx file. The raw data are in the WeitkampDistribution.csv and they are read into the model using the wrapper create\_THETAhjromta.r.

The distribution of adult Chinook salmon is based on the study by (Weitkamp 2010). To map the areas in Weitkamp (2010) to the areas in our model we used look-up Table 7. The distribution of smolts assumes that they are only available to predation during the month they entered freshwater in their area of origin, after which they entered a black box where they were unavailable to predators until the beginning of the next year.

Each area and run has a unique distribution but not all of the runs and areas in our model were represented by a particular stock in the Weitkamp (2010) results. To interpolate missing information we used the following rule based on discussions with Weitkamp (pers comm). : 1) spring and summer Chinook salmon tended to disperse further north than fall Chinook salmon, 2) fall Chinook salmon tended to remain near their area of origin and their distributions closely resembled neighboring areas, 3) recoveries of hatchery and wild fish had similar marine distributions, and 4) ocean age 1 fish were captured closer to the area of origin compared to older aged fish.  Based on these findings, if either spring or summer distributions for a particular area were missing, we assumed that spring and summer run distributions were the same and used which ever one was available..  If both the spring and summer runs were missing, we averaged the spring and summer runs from the closest adjacent area that had available tag information.  For areas with missing fall Chinook salmon tag information (e.g., mainland British Columbia to western Alaska), we assumed that 80% of the stock was distributed in the area of origin, and 10% was distributed to adjacent areas.  We assumed that winter Chinook salmon populations had the same distribution as fall Chinook salmon, and we assumed the “other” category, which is an aggregate of several stocks into a single release group, was an average across all observed and interpolated distributions.

Table 7. Lookup table for area IDs in our model and the hatchery IDs in Weitkamp (2010).

|  |  |  |
| --- | --- | --- |
| Area ID | Hatchery ID |  |
| Cen California | COLEMAN NFH Fall | TEHAMA-COLUSA FF Fall |
|  | FEATHER R HATCHERY Fall |  |
|  |  |  |
| Nor. Cal/Oregon | COLE RIVERS HATCHERY Fall | SALMON R HATCHERY Fall |
|  | COLE RIVERS HATCHERY Spri | TRASK R HATCHERY Fall |
|  | ELK R HATCHERY Fall | TRINITY R HATCHERY Fall |
|  | IRON GATE HATCHERY Fall | TRINITY R HATCHERY Spri |
|  | ROCK CR HATCHERY Spri |  |
|  |  |  |
| Columbia River | ABERNATHY SCDC HATCH Fall | PRIEST RAPIDS HATCHE Fall |
|  | BONNEVILLE HATCHERY Fall | SIMILKAMEEN HATCHERY Summ |
|  | COWLITZ SALMON HATCH Fall | SPRING CR NFH Fall |
|  | COWLITZ SALMON HATCH Spri | STAYTON PD (WILLAMET Fall |
|  | KLICKITAT HATCHERY Fall | WASHOUGAL HATCHERY Fall |
|  | LYONS FERRY HATCHERY Fall | Wells H/Sp Chan Summ |
|  | MARION FORKS HATCH Spri | WILLAMETTE HATCHERY Spri |
|  | MCKENZIE HATCHERY Spri | BONNEVILLE HATCHERY Late |
|  |  |  |
| outer Washington | FORKS CREEK HATCHERY Fall | IRRIGON HATCHERY Late |
|  | HOKO FALLS HATCHERY Fall | Quinault Lk & NFH Fall |
|  | HUMPTULIPS HATCHERY Fall | SOLDUC HATCHERY Spri |
|  |  |  |
| Salish Sea | ELWHA HATCHERY Fall | HOODSPORT HATCHERY Fall |
|  | Fraser abv Hope Spri | H-PUNTLEDGE R Fall |
|  | GROVERS CR HATCHERY Fall | H-PUNTLEDGE R Summ |
|  | H-BIG QUALICUM R Fall | H-QUESNEL R Summ |
|  | H-CAPILANO R Fall | H-QUINSAM R Fall |
|  | H-CHEHALIS R Fall | H-ROBERTSON CR Fall |
|  | H-CHEMAINUS R Fall | H-SHUSWAP R Summ |
|  | H-CHILLIWACK R Fall | H-SPIUS CR Spri |
|  | H-CLAYOQUOT Fall | H-TENDERFOOT CR Summ |
|  | H-CLEARWATER R UP/TO Summ | ISSAQUAH HATCHERY Fall |
|  | H-CONUMA R Fall | KENDALL CR HATCHERY Spri |
|  | H-COWICHAN R Fall | MARBLEMOUNT HATCHERY Spri |
|  | H-EAGLE R Summ | SAMISH HATCHERY Fall |
|  | H-GOLD R Fall | SOOS CREEK HATCHERY Fall |
|  | H-NANAIMO R Fall | WALLACE R HATCHERY Summ |
|  | H-NITINAT R Fall |  |
|  |  |  |
| WCVI/ BC | H-FORT BABINE Summ | H-OWEEKENO Summ |
|  | H-KINCOLITH R Spri | H-SNOOTLI CR Summ |
|  | H-KITIMAT R Spri | H-TERRACE Summ |
|  | H-MASSET Summ |  |
|  |  |  |
| Southeast AK | CRYSTAL LAKE Spri | NEETS BAY Spri |
|  | DEER MOUNTAIN Spri | SNETTISHAM Spri |
|  |  |  |
| Western AK | Cook Inlet Spri |  |

# Chinook salmon maturity-at-age and survival-at-age

The variables in the model for maturity-at-age and survival are and , respectively. The raw data are located in the files FRAM\_maturityAtAge.csv and FRAM\_survivalRates.csv, respectively, and the data from these files are read into the model with the wrappers create\_MAThra.r, create\_NCphjromyta.r, respectively. Summaries of the maturity and survival are in the worksheets “Table\_maturityAtAge” and “Table\_survivalAtAge” in the appendixTables.xlsx files. Note that the numbers in Table\_survivalAtAge are actually mortality estimates that are then transformed into survival estimates in the code.

In addition to predation, salmon are removed from the system through natural mortality and escapement. Estimates of maturity- and survival-at-age are based on FRAM model inputs. The mortality estimates from the FRAM model are only month and age-specific: all run types, origins, and salmon from different areas have the same survival rates. The maturation schedules are also based on the 78 distinct stocks FRAM model. The FRAM model is dominated by stocks from Puget Sound, and lacks any stocks from western or Southeast Alaska. For the western and southeast Alaska areas, we used the average maturation schedules from coastal British Columbia.

# Relationship between Chinook salmon energy, length, and mass

One of the key aspects of our model is transforming between energy as a function of length, and weight as a function of length or energy. The two key outcomes of our model are the number and biomass of Chinook salmon consumed. We know the length of Chinook salmon at different ages based on the FRAM model (Clemons et al. 2006). From O'Neill et al. (2014) we can use the equation in Figure 6, , to determine the energy of a Chinook salmon at a given length. Dividing the fraction of predator’s total energy derived from Chinook salmon of particular age by the energy content of Chinook salmon from that age yields the number of salmon consumed. To obtain an estimate of biomass consumed we use Equation 7 from Figure 3, . There is a second option for transforming energy into mass using the Equations in Figure 7; however, since we used a stock-aggregated relationship between length and energy, we felt it was appropriate to also use a stock-aggregate relationship between mass and energy.

# References

Adams, J., Kaplan, I.C., Chasco, B., Marshall, K.N., Acevedo-Gutiérrez, A., and Ward, E.J. 2016. A century of Chinook salmon consumption by marine mammal predators in the Northeast Pacific Ocean. Ecol. Inform. **34**: 44–51.

Allen, B.M., and Angliss, R.P. 2013. Killer whale (Orcinus orca): Eatern North Pacific Alaska Resident Stock. Technical Memorandum, NOAA.

Angliss, R.P., and Allen, B.M. 2015. Alaska marine mammal stock assessments, 2014. NOAA Technical Memorandum, NOAA, Seattle, WA. Available from http://www.nmfs.noaa.gov/pr/sars/pdf/alaska2014\_final.pdf [accessed 5 July 2016].

Barrett-Lennard, L.G., Heise, K., Saulitis, E., Ellis, G., and Matkin, C. 1995. The impact of killer whale predation on Steller sea lion populations in British Columbia and Alaska. Rep. North Pac. Univ. Mar. Mammal Res. Consort. Univ. Br. Columbia Vanc. BC Can.

Bigg, M.A. 1969. The harbour seal in British Columbia. Fisheries Research Board of Canada Ottawa. Available from http://library.wur.nl/WebQuery/clc/409938 [accessed 13 March 2016].

Bigg, M.A. 1985. Status of the Steller sea lion (Eumetopias jubatus) and California sea lion (Zalophus californianus) in British Columbia. Department of Fisheries and Oceans Ottawa. Available from http://www.racerocks.ca/wp-content/uploads/2014/03/sealionbigg17899.pdf [accessed 29 November 2016].

Boulva, J., McLaren, I.A., and others. 1979. Biology of the harbor seal, Phoca vitulina, in eastern Canada. Dept. of Fisheries and Oceans. Available from http://agris.fao.org/agris-search/search.do?recordID=US201300581218 [accessed 13 March 2016].

Boveng, P.L., Bengtson, J.L., Withrow, D.E., Cesarone, J.C., Simpkins, M.A., Frost, K.J., and Burns, J.J. 2003. The abundance of harbor seals in the Gulf of Alaska. Mar. Mammal Sci. **19**(1): 111–127.

Boyd, I.L. 2002. Estimating food consumption of marine predators: Antarctic fur seals and macaroni penguins. J. Appl. Ecol. **39**(1): 103–119.

Browne, P., Laake, J.L., and DeLong, R.L. 2002. Improving pinniped diet analyses through identification of multiple skeletal structures in fecal samples. Fish. Bull. **100**(3): 423–433.

Canadian Science Advisory Secretariat. 2010. Population assessment: Pacific harbour seal ( Phoba vitulina Richardsi). Scientific Advisory Report, Fisheries and Oceans Canada, Pacific Region. Available from http://www.dfo-mpo.gc.ca/Library/338997.pdf [accessed 13 March 2016].

Carmichael, R.W., Hoffnagle, T., Feldhaus, J., Eddy, D., and Albrecht, N. (n.d.). Upper Grande Ronde River Spring Chinook Salmon Hatchery Program Review. Oregon Department of Fish and Wildlife, 203 Badgley Hall, EOU,La Grande OR 97850. Available from https://www.fws.gov/lsnakecomplan/reports/ODFW/Eval/Upper%20Grande%20Ronde%20River%20Spring%20Chinook%20Salmon%20Hatchery%20Review%20FINAL.pdf.

Carretta, J.V., Oleson, E.M., Baker, J., Weller, D.W., Lang, A.R., Forney, K.A., Muto, M.M., Hanson, B., Orr, A.J., Huber, H., and others. 2015. US PACIFIC DRAFT MARINE MAMMAL STOCK ASSESSMENTS: 2015. Available from http://www.nmfs.noaa.gov/pr/sars/pdf/pac2015\_draft.pdf [accessed 16 May 2016].

Center for Whale Research. 2016. Study of Southern Resident Killer Whales. Available from http://www.whaleresearch.com/ [accessed 13 March 2016].

Clemons, E., Conrad, R., Simmons, C.D., Sharma, R., Grover, A., and Yuen, H. 2006. FISHERY REGULATION ASSESSMENT MODEL (FRAM). Available from http://www.pcouncil.org/bb/2006/0606/G1a\_FRAM\_Att\_2.pdf [accessed 13 March 2016].

Codde, S., and Allen, S. 2015. Pacific harbor seal (Phoca vitulina richardsi) monitoring at Point Reyes National Seashore and Golden Gate National Recreation Area. 2012 Annu. Rep. Available Httpwww Sfnps Orgdownloadprod Uct44500 Accessed May **2**.

Department of Fisheries and Oceans. 2014. 2014 Fraser River Stock Assessment and Fishery Summary Chinook, Coho, and Chum. Available from http://frafs.ca/sites/default/files/2014%20Post-season%20Fraser%20CN%20CO%20and%20CH.pdf.

DFO. 1999. Fraser River Chinook Salmon. DFO Science. Available from http://www.dfo-mpo.gc.ca/csas/Csas/status/1999/D6-11e.pdf.

Edgell, T.C., and Demarchi, M.W. 2012. California and Steller sea lion use of a major winter haulout in the Salish Sea over 45 years. Mar. Ecol. Prog. Ser. **467**: 253–262.

Ford, J.K., and Ellis, G.M. 2006. Selective foraging by fish-eating killer whales Orcinus orca in British Columbia. Mar. Ecol. Prog. Ser. **316**: 185–199.

French, S.S., González-Suárez, M., Young, J.K., Durham, S., and Gerber, L.R. 2011. Human disturbance influences reproductive success and growth rate in California sea lions (Zalophus californianus). PLoS One **6**(3): e17686.

Hanson, Mb., Baird, R.W., Ford, J.K., Hempelmann-Halos, J., Van Doornik, D.M., Candy, J.R., Emmons, C.K., Schorr, G.S., Gisborne, B., Ayres, K.L., and others. 2010. Species and stock identification of prey consumed by endangered southern resident killer whales in their summer range. Endanger. Species Res. **11**(1): 69–82.

Härkönen, T., and Heide-Jørgensen, M.-P. 1990. Comparative life histories of East Atlantic and other harbour seal populations. Ophelia **32**(3): 211–235.

Hauser, D.D., Logsdon, M.G., Holmes, E.E., VanBlaricom, G.R., and Osborne, R.W. 2007. Summer distribution patterns of southern resident killer whales Orcinus orca: core areas and spatial segregation of social groups. Mar. Ecol.-Prog. Ser.- **351**: 301.

Heard$^1$, W.R., Shevlyakov, E., Zikunova, O.V., and McNicol, R.E. 2007. Chinook salmon–trends in abundance and biological characteristics. Bull. No **4**: 77–91.

Henderson, M.A., and Graham, C.C. 1998. History and status of Pacific salmon in British Columbia. North Pac. Anadromous Fish Comm. Bull. **1**: 13–22.

Hernández-Camacho, C.J., Aurioles-Gamboa, D., and Gerber, L.R. 2008. Age-specific birth rates of California sea lions (Zalophus californianus) in the Gulf of California, Mexico. Mar. Mammal Sci. **24**(3): 664–676.

Herreman, J.K., Blundell, G.M., and Ben-David, M. 2009. Evidence of bottom-up control of diet driven by top-down processes in a declining harbor seal Phoca vitulina richardsi population. Mar. Ecol. Prog. Ser. **374**: 287–300.

Howard, S., Lance, M.M., Jeffries, S.J., and Acevedo-Gutiérrez, A. 2013. Fish consumption by harbor seals (Phoca vitulina) in the San Juan Islands, Washington. Fish. Bull. **111**(1): 27.

Jeffries, S., Huber, H., Calambokidis, J., and Laake, J. 2003. Trends and status of harbor seals in Washington State: 1978-1999. J. Wildl. Manag.: 207–218.

Jeffries, S., Smultea, M., Bacon, C., Jefferson, T., Mate, B., Irvine, L., and Follett, T. 2014. Aerial Surveys of Pinniped Haulout Sites in the PNW; Marine Mammal Aerial Surveys Conducted in the PNW, IPSW; and Offshore Large Whale Satellite Tagging in the NWTRC. Draft report, Naval Facilities Engineering Command, Northwest (NAVFAC NW), Silverdale, WA.

Jemison, L.A., Pendleton, G.W., Wilson, C.A., and Small, R.J. 2006. Long-term trends in harbor seal numbers at Tugidak Island and Nanvak Bay, Alaska. Mar. Mammal Sci. **22**(2): 339–360.

Kiefer, R.B., Bunn, P.R., and Johnson, J.L. 2002. Natural production monitoring and evaluation. Idaho Department of Fish & Game. Available from https://collaboration.idfg.idaho.gov/FisheriesTechnicalReports/Res03-30Kiefer2003%20Natural%20Production%20Monitoring%20and%20Evaluation.pdf [accessed 23 December 2016].

Kinsel, C., Zimmerman, M., Kishimoto, L., and Topping, P. 2008. Annual report: 2007 Skagit River salmon production evaluation. Wash. Dep. Fish Wildl. Olymp. Available from http://docs.streamnetlibrary.org/CoastalCutthroatData/sn600431.pdf [accessed 23 December 2016].

Kiyohara, K., and Volkhardt, G. 2008. Evaluation of downstream migrant salmon production in 2007 from the Cedar River and Bear Creek. Washington Department of Fish and Wildlife, Fish Program, Science Division. Available from http://dfw.wa.gov/publications/00090/wdfw00090.pdf [accessed 23 December 2016].

Maniscalco, J.M., Wynne, K., Pitcher, K.W., Hanson, M.B., Melin, S.R., and Atkinson, S. 2004. The occurrence of California sea lions (Zalophus californianus) in Alaska. Aquat. Mamm. **30**(3): 427–433.

Mathews, E.A., and Pendleton, G.W. 2006. Declines in harbor seal (Phoca vitulina) numbers in Glacier Bay national park, Alaska, 1992–2002. Mar. Mammal Sci. **22**(1): 167–189.

Matkin, C.O., Ellis, G., Olesiuk, P., and Saulitis, E. 1999. Association patterns and inferred genealogies of resident killer whales, Orcinus orca, in Prince William Sound, Alaska. Fish. Bull. **97**(4): 900–919.

Matkin, C.O., Ward Testa, J., Ellis, G.M., and Saulitis, E.L. 2014. Life history and population dynamics of southern Alaska resident killer whales (Orcinus orca). Mar. Mammal Sci. **30**(2): 460–479.

McPherson, S., Bernard, D., Clark, J.H., Pahlke, K., Jones, E., Der Hovanisian, J., Weller, J., and Ericksen, R. 2003. Stock status and escapement goals for Chinook salmon stocks in Southeast Alaska. Alsk. Dep. Fish Game Spec. Publ. (03–01): 03–01.

Muto, M.M., V. T. Helker, R. P. Angliss, B. A. Allen, P. L. Boveng,J. M. Breiwick, M. F. Cameron, P. J. Clapham, S. P. Dahle, M. E. Dahlheim, B. S. Fadely, M. C. Ferguson, L. W. Fritz, R. C. Hobbs, Y. V. Ivashchenko, A. S. Kennedy, J. M. London, S. A. Mizroch, R. R. Ream, E. L. Richmond, K. E. W. Shelden, R. G. Towell, P. R. Wade, and J. M. Waite, and A. R. Zerbini. 2016. Alaska Marine Mammal Stock Assessments, 2015. Technical Memorandum, NOAA, Seattle, WA.

National Marine Fisheries Service. 2008. Recovery Plan for Southern Resident Killer Whales (Orcinus orca). National Marine Fisheries Service, Northwest Region, Seattle, Washington. Available from http://www.beamreach.org/data/101/Science/processing/Nora/Papers/SRKW-Recov-Plan-Final.pdf [accessed 3 September 2016].

National Marine Fisheries Service (NMFS). 1997. Investigation of Scientific Information on the Impacts of California Sea Lions and Pacific Harbor Seals on Salmonids and on the Coastal Ecosystems of Washington, Oregon, and California. Available from http://www.nwfsc.noaa.gov/publications/scipubs/techmemos/tm28/mammal.htm [accessed 13 March 2016].

Nichol, L.M., and Shackleton, D.M. 1996. Seasonal movements and foraging behaviour of northern resident killer whales (Orcinus orca) in relation to the inshore distribution of salmon (Oncorhynchus spp.) in British Columbia. Can. J. Zool. **74**(6): 983–991.

Noren, D.P. 2011. Estimated field metabolic rates and prey requirements of resident killer whales. Mar. Mammal Sci. **27**(1): 60–77.

Olesiuk, P.F., Ellis, G.M., and Ford, J.K. 2005. Life history and population dynamics of northern resident killer whales (Orcinus orca) in British Columbia. Canadian Science Advisory Secretariat. Available from https://www.researchgate.net/profile/John\_Ford23/publication/283854825\_Life\_History\_and\_Population\_Dynamics\_of\_Northern\_Resident\_Killer\_Whales\_Orcinus\_orca\_in\_British\_Columbia/links/5648ae9808ae9f9c13eb9c42.pdf [accessed 16 May 2016].

O�Neill, S.M., Ylitalo, G.M., and West, J.E. 2014. Energy content of Pacific salmon as prey of northern and southern resident killer whales. Endanger. Species Res. **25**: 265–28.

PACIFIC SALMON COMMISSION JOINT SALMON. 2016. ANNUAL REPORT OF CATCH AND ESCAPEMENT FOR 2015. Pacific Salmon Comission, Portland, Oregon. Available from http://www.psc.org/publications/technical-reports/technical-committee-reports/chinook/.

Peterson, S.H., Lance, M.M., Jeffries, S.J., and Acevedo-Gutiérrez, A. 2012. Long distance movements and disjunct spatial use of harbor seals (Phoca vitulina) in the inland waters of the Pacific Northwest. PloS One **7**(6): e39046.

Pitcher, K.W., and Calkins, D.G. 1979. Biology of the harbor seal, Phoca vitulina richardsi, in the Gulf of Alaska. Outer Continental Shelf Environmental Assessment Program, US Department of Interior, Bureau of Land Management. Available from http://www.data.boem.gov/PI/PDFImages/ESPIS/0/313.pdf [accessed 13 March 2016].

Pitcher, K.W., Olesiuk, P.F., Brown, R.F., Lowry, M.S., Jeffries, S.J., Sease, J.L., Perryman, W.L., Stinchcomb, C.E., and Lowry, L.F. 2007. Abundance and distribution of the eastern North Pacific Steller sea lion (Eumetopias jubatus) population. Fish. Bull. **105**(1): 102–116.

PSC. 2016. Review of 2015 Ocean Salmon Fisheries: Stock Assessment and Fishery Evaluation Document for the Pacific Coast Salmon Fishery Management Plan. Pacific Fishery Management Council, Portland, Oregon.

RMIS. 2012. Regional Mark Information System User Guide. Pacific Fishery Management Council, Portland, Oregon. Available from http://www.rmpc.org/files/RMIS\_UserGuide\_V3.pdf.

Scordino, J. 2010. West coast pinniped program investigations on California sea lion and Pacific Harbor seal impacts on salmonids and other fishery resources. Pacific States Marine Fisheries Commission. Available from http://www.westcoast.fisheries.noaa.gov/publications/protected\_species/marine\_mammals/pinnipeds/sea\_lion\_removals/expand\_pinniped\_report\_2010.pdf [accessed 13 July 2016].

Scordino, J., Akmajian, A.M., and Riemer, S.D. 2014. California and Steller sea lion diets in northwest Washington, 2010-2013.

Seiler, D., Volkhardt, G., Fleischer, L., and Kiyohara, K. 2005. Evaluation of downstream migrant salmon production in 2001 from the Cedar River and Bear Creek. Washington Department of Fish and Wildlife, Fish Program, Science Division. Available from http://wdfw.wa.gov/publications/00084/wdfw00084.pdf [accessed 26 October 2016].

Seiler, D., Volkhardt, G., Topping, P., Fleischer, L., Miller, T., Schonning, S., Rawding, D., Groesbeck, M., Woodard, R., and Hawkins, S. 2004. 2003 Juvenile Salmonid Production Evaluation Report Green River, Wenatchee River, and Cedar Creek. Available from http://dfw.wa.gov/publications/00067/wdfw00067.pdf [accessed 23 December 2016].

Sigler, M.F., Tollit, D.J., Vollenweider, J.J., Thedinga, J.F., Csepp, D.J., Womble, J.N., Wong, M.A., Rehberg, M.J., and Trites, A.W. 2009. Steller sea lion foraging response to seasonal changes in prey availability. Mar. Ecol. Prog. Ser. **388**: 243–261.

Small, R.J., Pendleton, G.W., and Pitcher, K.W. 2003. Trends in abundance of Alaska harbor seals, 1983–2001. Mar. Mammal Sci. **19**(2): 344–362.

Stansell, R.J., Gibbons, K.M., and Nagy, W.T. 2010. Evaluation of pinniped predation on adult salmonids and other fish in the Bonneville Dam tailrace, 2008-2010. US Army Corps of Engineers, Bonneville Lock and Dam. Available from http://www.salmonrecovery.gov/Files/2011%20APR%20files/New%20folder%20(2)/Stansell\_et\_al.\_2011\_S1-2008-2010\_Pinniped\_Report.pdf [accessed 5 July 2016].

Suryan, R.M., and Harvey, J.T. 1998. TRACKING HARBOR SEALS (PHOCA VITULINA RICHARDSI) TO DETERMINE DIVE BEHAVIOR, FORAGING ACTIVITY, AND HAUL-OUT SITE USE. Mar. Mammal Sci. **14**(2): 361–372.

Thomas, A.C., Nelson, B., Lance, M.M., Deagle, B., and Trites, A. 2016. Harbour seals target juvenile salmon of conservation concern. Can. J. Fish. Aquat. Sci.

Tollit, D.J., Wong, M.A., and Trites, A.W. 2015. Diet composition of Steller sea lions (Eumetopias jubatus) in Frederick Sound, southeast Alaska: a comparison of quantification methods using scats to describe temporal and spatial variabilities. Can. J. Zool. **93**(5): 361–376.

Trites, A.W., and Donnelly, C.P. 2003. The decline of Steller sea lions Eumetopias jubatus in Alaska: a review of the nutritional stress hypothesis. Mammal Rev. **33**(1): 3–28.

Ward, E.J., Dahlheim, M.E., Waite, J.M., Emmons, C.K., Marshall, K.N., Chasco, B.E., and Balcomb, K.C. 2016. Long-distance migration of prey synchronizes demographic rates of top predators across broad spatial scales. Ecosphere **7**(2). Available from http://onlinelibrary.wiley.com/doi/10.1002/ecs2.1276/full [accessed 5 July 2016].

Ward, E.J., Holmes, E.E., and Balcomb, K.C. 2009. Quantifying the effects of prey abundance on killer whale reproduction. J. Appl. Ecol. **46**(3): 632–640.

Weise, M.J., and Harvey, J.T. 2008. Temporal variability in ocean climate and California sea lion diet and biomass consumption: implications for fisheries management. Mar. Ecol. Prog. Ser. **373**: 157–172.

Weitkamp, L.A. 2010. Marine distributions of Chinook salmon from the west coast of North America determined by coded wire tag recoveries. Trans. Am. Fish. Soc. **139**(1): 147–170.

Williams, T.M., Estes, J.A., Doak, D.F., and Springer, A.M. 2004. Killer appetites: assessing the role of predators in ecological communities. Ecology **85**(12): 3373–3384.

Winship, A.J., Hunter, A.M., Rosen, D.A., and Trites, A.W. 2006. Food consumption by sea lions: existing data and techniques. Sea Lions World Alsk. Sea Grant Coll. Program: 177–191.

Winship, A.J., Trites, A.W., and Calkins, D.G. 2001. Growth in body size of the Steller sea lion (Eumetopias jubatus). J. Mammal. **82**(2): 500–519.

Winship, A.J., Trites, A.W., and Rosen, D.A. 2002. A bioenergetic model for estimating the food requirements of Steller sea lions Eumetopias jubatus in Alaska, USA. Mar. Ecol. Prog. Ser. **229**: 291–312.

Womble, J.N., Pendleton, G.W., Mathews, E.A., Blundell, G.M., Bool, N.M., and Gende, S.M. 2010. Harbor seal (Phoca vitulina richardii) decline continues in the rapidly changing landscape of Glacier Bay National Park, Alaska 1992–2008. Mar. Mammal Sci. **26**(3): 686–697.

Wright, B.E., Brown, R.F., and Murtagh, T. 2015. WILLAMETTE FALLS PINNIPED MONITORING PROJECT, 2015. Oregon Department of Fish and Wildlife. Available from http://www.dfw.state.or.us/fish/SeaLion/docs/Willamette\_Falls\_2015\_sea\_lion\_report.pdf [accessed 16 December 2016].

York, A.E. 1994. The population dynamics of northern sea lions, 1975-1985. Mar. Mammal Sci. **10**(1): 38–51.

Zimmerman, M.S., Kinsel, C., Beamer, E., Connor, E.J., and Pflug, D.E. 2015. Abundance, survival, and life history strategies of juvenile Chinook Salmon in the Skagit River, Washington. Trans. Am. Fish. Soc. **144**(3): 627–641.

1. http://www.westcoast.fisheries.noaa.gov/publications/protected\_species/marine\_mammals/pinnipeds/sea\_lion\_removals/2017/mmpa\_section\_120\_program\_review\_20170208\_final.pdf [↑](#footnote-ref-1)