

Impact of Salmon Quantities on Lactating Northern Resident Killer Whales

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Abstract: In our study on northern resident killer whales (NRKW), we performed a power estimate on generated data to see how salmon abundance and pod size would impact lactating females. Only the simulated models for lactating females and pod size had statistical significance. While there was no clear relationship between lactating females and salmon abundance, more analysis with real data would be beneficial for more accurate results.

Introduction: Northern resident killer whales exclusively eat chum and chinook salmon and live in pods if maternally related. According to Stredulinsky et. al., assessing orca pod interactions has varying implications with resource availability (2021). We hypothesize that salmon abundance and pod size will influence the number of lactating female orcas in a pod. Orca whales nurse their calf for one to two years after they are born; therefore, we will be using lactating females as a measure of fecundity, defined as the number of births in the pod in a year (Tarsi, et al., 2012). From this hypothesis, we predict that higher salmon quantities will result in more lactating orcas since it provides more resources and gives them the opportunity to reproduce successfully. Previous studies have suggested that decreased availability of chinook salmon is a significant stressor for NRKWs, resulting in late pregnancy failure (Wasser et.al., 2017)(Ward et.al, 2009). We also predict that larger pod size will result in higher amounts of lactating females since we are more likely to see more females at reproductive age. However, this may depend on how strained the pods are for resources. While we planned to use orca and salmon abundance census data, the dataset we had access to was standardized and contained multiple negative values that we were unable to interpret. We contacted the authors for the raw data but, due to time constraints, were unable to fully develop our research with it. A supplementary analysis can be found in the Appendix 2.

Methods

Data Description: To generate salmon data, the maximum and minimum chum and chinook salmon abundances were found from commercial counts (Irvine et al., 2009) and values in millions of fish were randomly sampled between those maximum and minimums over 31 years (1980-2010). The data for the total number of orcas was generated by approximating 300 total orcas in the population as of 2019. To allow the number of orcas to change each year, the total orcas in the population (s) was determined via a poisson distribution with $\lambda = 300$. A multinomial distribution was used to generate the number of orcas in 16 pods (pod_size) where the size was equal to s with each pod size being equally likely. Lactating orcas for each pod (Lactating_females) was generated as a poisson distribution, where $\lambda = \beta_1 \cdot \text{pod size} + \beta_2 \cdot \text{total salmon}$. β_1 is the effect that pod size has on lactating females, from 0.2 to 0.24, which is the average number of females in the pod that are of reproductive age. β_2 is a vector with values from 0.0000001 to 0.1, which are the estimated effect sizes of salmon abundance. Generalized linear mixed models were created for all combinations of β_1 and β_2 since random effects are included in the model and not all assumptions for a linear mixed model were met.

Assumptions: Commercially caught salmon data from BC was used as a proxy for ocean abundance as it is difficult to find open access data sources for salmon quantities (Irvine et al., 2009). Additionally, it was assumed salmon were not influenced by the year in our model for

simplicity. In terms of orca data it was assumed all pod sizes were equally likely to occur whereas in reality large pods are unlikely to stay together for long periods. Orca populations were assumed to follow a poisson distribution with a mean of 300 individuals. Finally, the number of lactating females was estimated to range from 20-24% of reproductive age females based on calculations provided by (COSEWIC, 2008). Within this percentage it is assumed lactating females will not be giving birth while nursing.

Data Analysis: As stated above a generalized linear mixed model with a poisson distribution was repeated 1000 times. The GLMM is as follows:

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glmer(lactating_females~total_salmon+pod_size+(1|group_number)+(1|year),
      family = poisson, data)
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The fixed variables are total salmon abundance (chinook and chum) and pod size; we are looking to see how these variables impact lactating females. **The random variables** are pod number and the year. They needed to be included because they would contribute to some variance.

Results: There were 30 GLMM's with various parameters (See Table 1). Figure 1 predicts that as pod size increases the number of lactating females is likely to increase as well. Figure 2 does not have a clear trend. The results of this power analysis allowed us to *reject the null hypothesis* that pod size does not impact the number of lactating female orcas, but we *failed to reject the null* that salmon abundance does not impact the number of lactating female orcas

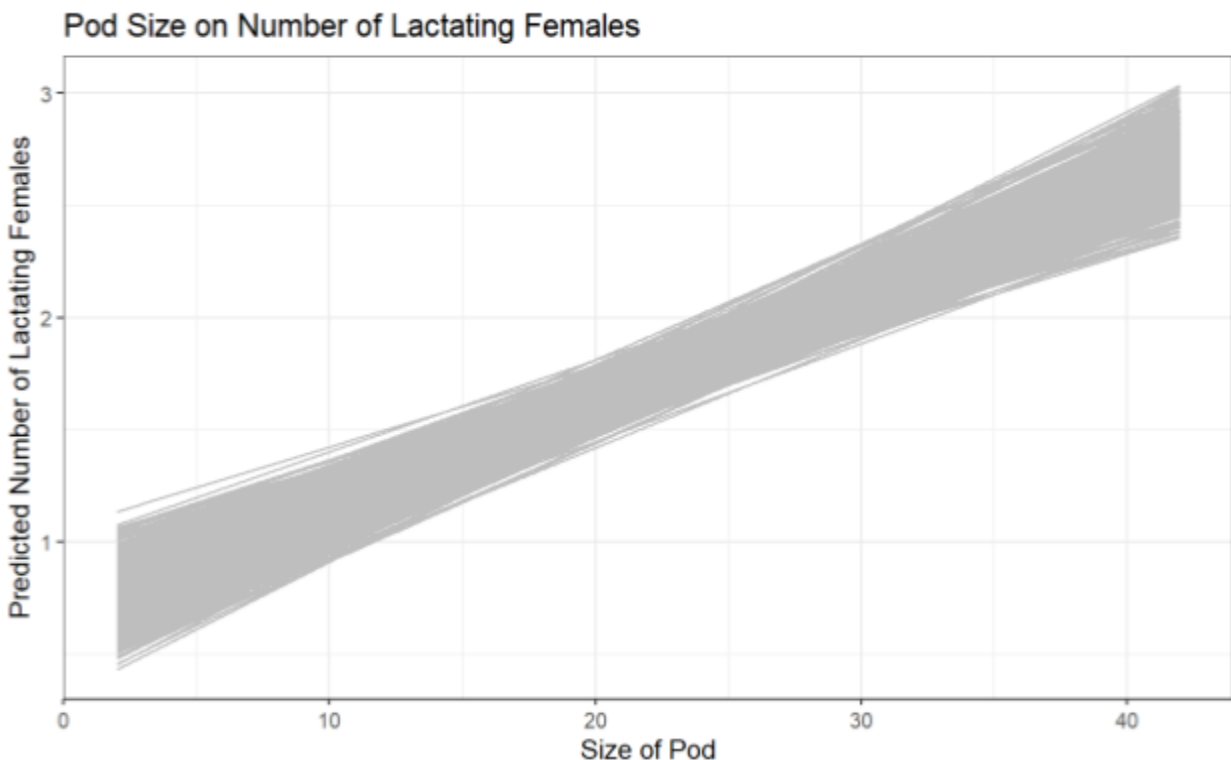


Figure 1- Effect of Pod Size on Number of Lactating Females. This graph shows 30 GLMM's with various parameters (see Table 1). Each GLMM was repeated 1000 times for a total of 30,000 simulations. The slope and intercept of each model is graphed here. We can predict an increase in lactating females as the pod size increases.

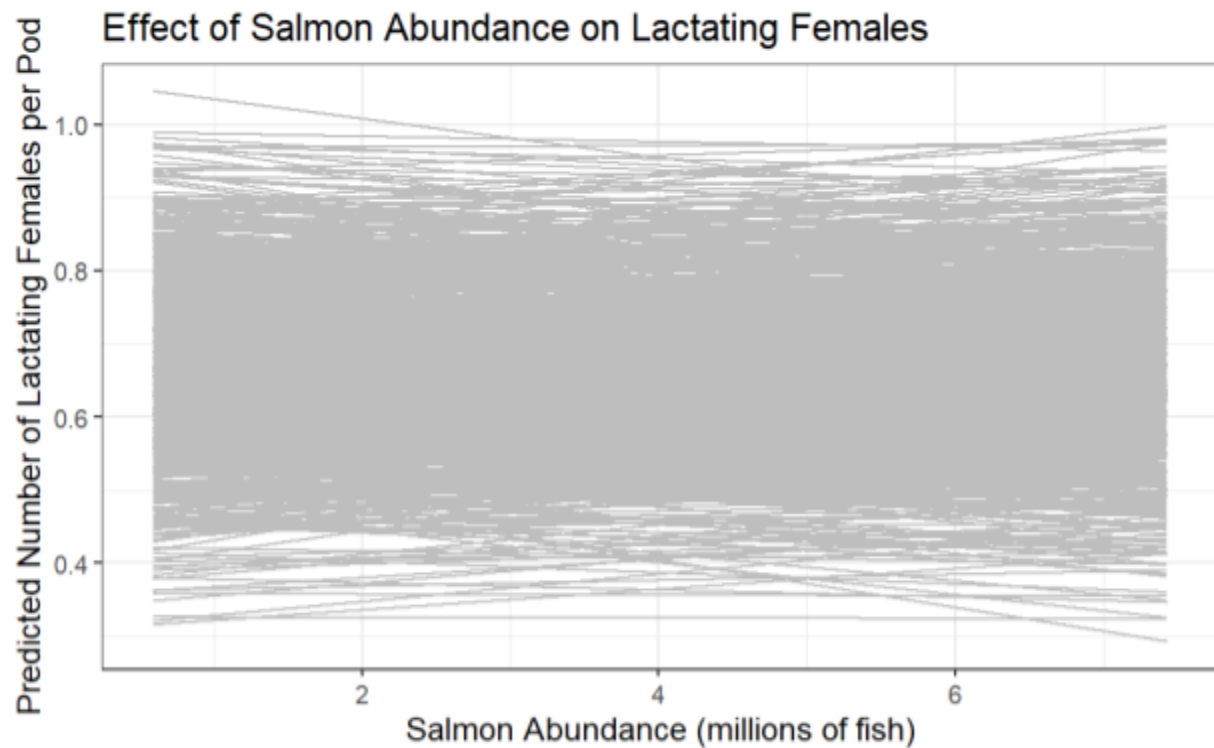


Figure 2- Effect of Salmon Abundance on Lactating Females. There were 30 GLMM with various parameters (See Table 1). These 30 models were ran 1000 times for a total of 30,000 models. The slope and intercept of each model is graphed here. There is not clear trend between abundance of salmon and lactating females. Each model appears to have different results.

Table 1- Power Estimates of Pod and Salmon Effect size

Power Estimate Salmon	Power Estimate Pod	Beta 1 (Effect of Pod Size)	Beta 2 (Effect of Salmon)
0.046	1	0.2	$1e^{-07}$
0.039	1	0.21	$1e^{-07}$
0.043	1	0.22	$1e^{-07}$
0.040	1	0.23	$1e^{-07}$
0.037	1	0.24	$1e^{-07}$
0.053	1	0.20	$1e^{-05}$
0.046	1	0.21	$1e^{-05}$
0.045	1	0.22	$1e^{-05}$

0.041	1	0.23	1e ⁻⁰⁵
0.046	1	0.24	1e ⁻⁰⁵
0.044	1	0.20	1e ⁻⁰⁴
0.055	1	0.21	1e ⁻⁰⁴
0.043	1	0.22	1e ⁻⁰⁴
0.061	1	0.23	1e ⁻⁰⁴
0.040	1	0.24	1e ⁻⁰⁴
0.048	1	0.20	1e ⁻⁰³
0.042	1	0.21	1e ⁻⁰³
0.045	1	0.22	1e ⁻⁰³
0.052	1	0.23	1e ⁻⁰³
0.052	1	0.24	1e ⁻⁰³
0.039	1	0.20	1e ⁻⁰²
0.044	1	0.21	1e ⁻⁰²
0.028	1	0.22	1e ⁻⁰²
0.046	1	0.23	1e ⁻⁰²
0.046	1	0.24	1e ⁻⁰²
0.035	1	0.20	1e ⁻⁰¹
0.040	1	0.21	1e ⁻⁰¹
0.044	1	0.22	1e ⁻⁰¹
0.037	1	0.23	1e ⁻⁰¹
0.036	1	0.24	1e ⁻⁰¹

Table 1: Power estimates and associated parameters sizes. Beta 1 represents the effect of the pods size, Beta 2 represents the effect of salmon size. There are 30 rows representing the 30 GLMM combinations. Each GLMM was run 1000 times to generate the power estimates. The power estimate of the salmon is calculated by taking the models that were statistically significant (having a $p < 0.05$) and dividing them by the 1000 other models with the same parameter. In other words a value of 0.046 corresponds to 46 of the 1000 models having statistically significant results at set Beta values.. The same process was

repeated for the power estimates of the pod. In the case of the pods, a value of 1 corresponds to 1000 of 1000 models being statistically significant.

Discussion: Pod size impacts the number of lactating female orcas. This result is supported by figure 1 which shows a positive correlation with the number of lactating females and pod size. The power estimate is 1, showing all simulations are significant. However, the following conclusions are hindered by the lack of real data and therefore, the reality may be the opposite given the use of generated salmon and lactating orca data. Knowledge of how fecundity is impacted by pod size is important for conservation purposes because maintaining or increasing population numbers involves supporting healthy fecundity levels. This positive correlation is interesting since larger pods require a greater division in resources, decreasing the amount of food available to lactating orcas during a period where they are expected to increase their caloric needs by 50% (Stredulinsky et al., 2021). However, NRKWs are thought to be good at sharing resources and there may be a lesser need to split into smaller pods, despite the many reasons to do so, including competition for resources, reduction in relatedness, and accumulation of experienced females (Stredulinsky et al., 2021) (Wright, et al., 2016).

The result that salmon abundance influences the number of lactating females is based on both simulated salmon and lactating orca data, so the conclusions are unclear (see figure 2). However, if this data had been true census data, it is surprising food availability does not influence the number of lactating females because of the increase in resources the lactating female needs. Therefore, it is likely food availability is positively correlated with the number of lactating females. However, the age distribution of the pod, availability of a suitable mate and many other confounding variables could hinder our ability to get a significant result from only salmon abundance. In addition, salmon abundance is likely decreasing through time; therefore, there would likely be a positive correlation of decreasing lactating females (EPA, 2021). Finally, these conclusions are hindered by our likely failure to meet the assumptions discussed above and our lack of real data. More analysis with real observations would be beneficial for more conclusive results.

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Appendices and Supplementary Material:

A1: Description of Data File

A2: Orca Census Data Analysis from Dr. Thomas Doniol-Valcroze (DFO Cetacean Research)

*See Github for Code: Titled “**Orca-Data-Generation-Final**” - This is our final code; our rough work/thought process is included in the code file listed below.

* “**Orca-Data-Final-Incl-Old-Hypothesis**” is the R code for before we generated our own model. This was when we were still basing it on Stredulinsky’s data, our exploration can be seen here if needed.

Appendix 1: Data File Description

*Only data columns used in analysis or explored were described (because we subsetting the data and because a data file description for the census data was not provided.)

From Stredulinsky:

- Year (1980-2010)
- Group ID (Pod Identification number)
- CK.0a (Chinook salmon ocean abundance)

- CK.tr (Chinook salmon terminal run reconstruction)
- CM (chum salmon terminal run abundance index)
- DPerg (estimated daily prey energetic requirement of pod)(kilocalories)
- FLg (Number of lactating females in the pod (as proportion to pod size)
- FRg (Number of reproductive-age females in the pod (proportion of pod size)
- Ng (Number of individuals in pod)

From “Orca-Data-Generation-Final”

- PowersSalmon (Power estimate of salmon- # of significant models (p value <0.05)/ total models run (1000))
- powEstPod (Power estimate of pod- (same calculation as Powers Salmon)
- beta1 (Effect size of Pod on lactating females (0.2-0.24 From COSEWIC))
- beta2 (Effect size of salmon abundance on lactating females (range from 0.00001 - 0.1, various discrete models))
- Salmon Abundance - (Sum of abundance data from Chinook and Chum data)

From DFO Cetacean Research Census Data

- YEAR
- Size_best (Estimate for total population size)
- Females_fecund_unavailable (Number of lactating females... because they are no longer fecund currently)
- Birth_count (Number of Births)
- Pregnancy_count (number of pregnant orcas)

From “Orca-Census-Data-Final”

- Year
- Pod_Num (numerical identity of a pod in a year)
- Pod_Size_Multinom (size of the pod)
- Fecund_Unav_Multinom (females with fecundity unavailable in the pod)
- Births_Multinom (births in a pod)
- Pregnancy_Multinom (pregnancies in a pod)
- Chinook_Abundance (abundance of chinook salmon in millions of fish)
- Chum_Abundance (abundance of chum salmon in millions of fish)
- Total_Salmon (total abundance of salmon)

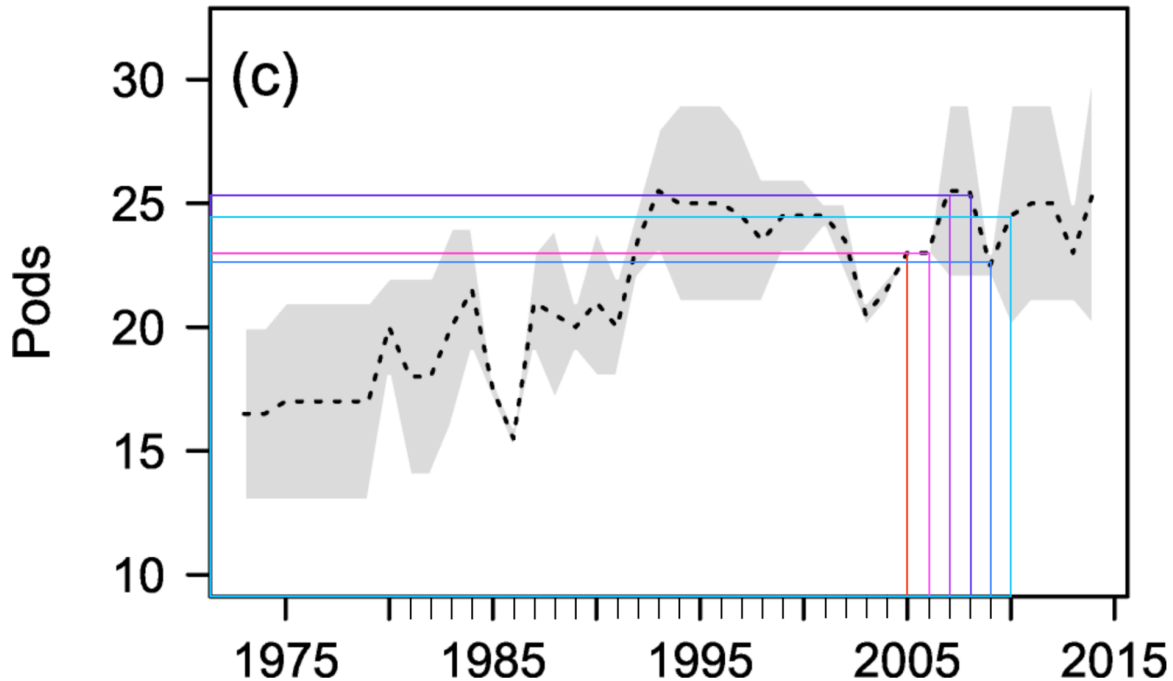
Appendix 2: Orca Census Data Analysis from DFO Cetacean Research

*See Code labeled “**OrcaCensusDataWork**” on Github

DFO Cetacean Research NRKW Census Data includes data about the NRKW population for each year from 1973-2022. The values used in the analysis are YEAR, Size_best, Females_fecund_unavailable, Birth_count, and Pregnancy_count. The values are given for the total population in each year, and are not split into pods. Females_fecund_unavailable, Birth_count, and Pregnancy_count are used as potential proxies for lactating females since there is no official value measuring that.

To determine the number of pods, two approaches were considered. One was to count the number of pods measured for each year in the original data set, but this only includes the pods

the authors measured (the selection criteria is not entirely clear). The other was to use Fig. 1c from Stredulinsky et. al. 2021. This graph shows a line representing the total number of groups over time, but does not give exact values. Pod sizes for each year were estimated using added minor ticks determined by the pixel width between major ticks on the x-axis and then using straight lines with 90° angles to find corresponding values on the y-axis. An example showing estimations from 2005-2010 is below.



In a given year, the size of each pod, number of females with fecundity unavailable, pregnancy count, and birth count are determined via multinomial distributions. The size for each multinomial distribution is the total from that year with an equal probability for each pod in that year. These were saved in columns labeled.

Salmon data generation is identical to that in Appendix 1, and as described in data analysis.

Histograms were created for Fecund_Unav_Multinom, Births_Multinom, Pregnancy_Multinom, Pod_Size_Multinom, and Total_Salmon to assess normality for modeling purposes. Pod_Size_Multinom was normally distributed but the rest were not. Since random effects are included, GLMMs were performed.

Six GLMMs were run. The results of the Orca census data were not significant.

- 1) Birth Count~Salmon Abundance + Pod Size + (1|Year) + (1|Pod ID)
 - a) Not significant for Salmon Abundance or Pod Size on Birth Count.
- 2) Pregnancy Count~Salmon Abundance + Pod Size + (1|Year) + (1|Pod ID)
 - a) Not significant for Salmon Abundance or Pod Size on Pregnancy Count
- 3) Number of Lactating Females~ Salmon Abundance + Pod Size (1|Year) + (1|Pod ID)
 - a) Not significant for Salmon Abundance or Pod Size on the number of lactating females
- 4) Birth Count~Salmon Abundance + Pod Size + Total Population +(1|Year) + (1|Pod ID)
 - a) Not significant for Pod Size or Salmon Abundance on Birth Count. Significant for total population on Birth Count with a p-value of $2.29e^{-5}$.

- 5) Pregnancy Count~Salmon Abundance + Pod Size + Total Population +(1|Year) + (1|Pod ID)
 - a) Not significant for Salmon Abundance or Pod Size on the number of pregnant orcas. But, significant for the total population on the number of pregnant females with a p-value of $2.46e^{-4}$.
- 6) Number of Lactating Females~Salmon Abundance + Pod Size + Total Population +(1|Year) + (1|Pod ID)
 - a) Not significant for Salmon Abundance or Pod Size on the number of pregnant orcas. But, significant for the total population on the number of pregnant females with a p-value of $8.14e^{-8}$.

The results of these GLMMs are interesting because salmon abundance and pod size do not impact any of the three measures of fecundity we chose to include in our analysis of the orca census data including the number of pregnant females, the number of births, and the number of lactating females within a year. Although we used lactation rates in our initial analysis, the new census data that was provided included birth and pregnancy counts which are more direct measures of fecundity. The fact that salmon does not have a significant impact on any measures of fecundity allows for minimal conclusions because the salmon data is generated; however, a somewhat more conclusive analysis can be formed. The pod size was partially based on real data, but partially randomized. As the pod size changes, fecundity is not altered. It is likely that a combination of confounding variables, the increasing splitting of resources, and this population of orca's ability to share resources creates this lack of a significant effect. Finally, the total orca population size has a significant effect on fecundity. This is likely because there are more orcas to successfully reproduce. Larger populations are more stable and resilient to demographic and environmental stochasticity (Fortin, 2023). For many reasons, increasing population sizes helps with the ability of a species to persist. For the northern resident killer whales, our significant GLMMs prove that larger populations will increase successful reproduction and therefore increase population sizes.