BROWN BEARS FACE GLOBAL WARMING

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ABSTRACT

Contents

List of Tables

List of Figures

Chapter 1

Introduction

At the beginning of the 20^{th} century, the global temperature trend of the earth changed directions and aided in the creation of a new lifestyle [Crowley, 2000]. When the industrial revolution began a significant amount of greenhouse gases were introduced into our atmosphere, which kept the heat from escaping [EPA, 2019]. We are now realizing the damage we have done to the earth and are trying to develop solutions to this problem without sacrificing our comfort. Unfortunately, the realization of this issue is a little later for other species such as polar and koala bears [Adams-Hosking et al., 2011, Wiig et al., 2008, Stirling and Derocher, 2012].

This thesis reviews a variety of nonlinear differential equation models while implementing Lotka-Volterra equations to simulate the effects of climate change on interactive species such as: brown bears with salmon, or even humans with agriculture. Nonlinear differential equations will be used to model species that follow logistic growth pattern. An inspiration of the Lotka-Volterra equation is used in representing the interaction between two species. The primary focus of this work is to display the effects of climate change and illustrate the potential dangers that may lie ahead if a solution isn't discovered.

Currently, some sea life animals are starting to experience the side effects of global warming. One species in particular facing the effects of sea temperature change are pacific salmon *Oncorhynchus*. Salmon live in the ocean, but when it is time to reproduce they swim up stream of rivers to lay their eggs and usually die shortly after, this is called spawning. Salmon like to begin their journey from salt water to fresh water between late spring and early summer, but this is dependent on the species and location of the salmon [ADFG, 2021]. Specifically in Alaska, salmon can be seen spawning in river streams between the middle of July through late October [Lisi et al., 2013]. Salmon are quite sensitive to their environment and are dependent on water temperatures [ADFG, 2021]. As the temperature rises, the time in which they spawn will change respectively. This doesn't seem like a big deal since in theory their spawning time will just change [ADFG, 2021]. Well, Alaskan brown bears feed off salmon during this time and this is a large portion of their diet.

Alaskan brown bears hibernate during winter and emerge during spring. Brown bears consume a lot of food during this time such as berries, roots of plants, squirrels, moose, caribou, and fish [ADFG, 2021]. Alaskan brown bears have many sources of food, but salmon is an important part of their diet, consuming an average of 1099 kg per year [Deacy et al., 2018, Hilderbrand et al., 1999]. If the change is sea temperature directly effects the lives of salmon, then we can expect to see the lives of those that depend on that food source to be negatively effected, like brown bears. Pacific salmon are already migrating further north where temperatures are more suitable for them [Taylor, 2008]. So, some ideas of these side effects consists of the migration of salmon to temperatures that better suit them therefore resulting in the possible migration of brown bears, replacement of salmon as a food source, or even a reduction in population if unable to compensate in the loss of a food source. In order for the brown bear population to live on, they will need to eventually adapt to this new environment they are approaching.

Chapter 2 briefly covers the background for the causes of global warming and the recorded effects of the increase in earth's temperature. This chapter also reviews specific differential equations that will be used in developing the appropriate model. It also discusses interaction between species by introducing the Lotka-Volterra equation.

Chapter 3 begins the model creation processes by constructing differential equations that illustrates the population of the brown bears, as well as the pacific salmon species in Alaska. Next, to incorporate the influence of temperature on salmon, a reproductive rate function is designed to reflect the change in reproduction depending on temperature. This chapter concludes with a final function that models water temperature change in Alaskan rivers and streams for the past 20 years.

Chapter 4 continues the model creation process by combining the individual functions and equations in chapter 3 to construct a model that demonstrates the outcome of the salmon and brown bear species over time.

Chapter 5 performs an analysis on the interaction model created in the chapter 4.

Chapter 6 discusses the results of the model and talks about potential result of the brown bear and salmon species.

Chapter 2

Background

2.1 Current State of Global Warming

The topic of climate change has been debated for many years. Some people believe that global warming is a myth and incorrectly use science to support their claim [Allchin, 2015]. As more evidence for global warming arises more minds are starting to shift the other way. It is now understood by many people and most scientists that the global temperature is likely to increase an average of 3.2°C by 2100 [Raftery et al., 2017]. A specific science committee developed a joint bayesian hierarchical model to reveal that there is a 5% chance the earth increases in temperature less than 2°C by 2100 [Raftery et al., 2017]. It is agreed upon that the blame of the increase in temperature belongs to CO_2 amongst other gasses created by human activities [Osterkamp and Lachenbruch, 1990]. In Alaska specifically, the 20^{th} century reflects a increasing trend of 2 - 4° C of the permafrost [Osterkamp and Lachenbruch, 1990]. In 1990 climate models predicted a warming of the climate of about 3 - 6° C by the middle of the 21^{st} century in Alaska

[Osterkamp and Lachenbruch, 1990]. The effects that will follow this dramatic temperature change will raise the average sea level, cause animals to migrate to new locations, threaten the population of animals that are sensitive to their climate conditions [Osterkamp and Lachenbruch, 1990, Adams-Hosking et al., 2011, Taylor, 2008]

Global warming becomes more serious as the years keep rolling by. The most recent wake up calls are the effects on polar and koala bears [Wiig et al., 2008, Adams-Hosking et al., 2011, Stirling and Derocher, 2012]. The permafrost in Alaska is melting which is causing damage to people's homes, roads, and pipelines [Osterkamp and Lachenbruch, 1990]. The population of polar bears are in a decline due to the melting of ice caps [Hunter et al., 2010]. The koala bears in Australia had to migrate to new locations due to the increase in wildfires [Adams-Hosking et al., 2011]. These are just a few significant events that are breaking out in the world due to global warming, but we can expect to see more as time goes on. Animals that are sensitive to their environment, such as many sea life, are under threat because the sea surface temperature is changing alongside the air temperature [Taylor, 2008, Hansen et al., 2010, Iz, 2018]. For example, Salmon in Alaska are experiencing higher rates of prespawning mortality because they are migrating to the creeks earlier due to the shift in their environmental temperatures [Bowerman et al., 2018]. If the temperatures continue to increase, then prespawning mortality will increase as well [Bowerman et al., 2018]. Scientists around the world have researched the causes for the sudden climb in temperature in hopes to find a solution to reverse the effects [EPA, 2019, Cook et al., 2016].

2.2 Reasons For The Change in Temperature

The topic of climate change has been debated for many years. Some people believe that global warming is a myth and incorrectly use science to support their claim [Allchin, 2015]. As more evidence for global warming arises more minds are starting to shift the other way. It is now understood by many people and most scientists that the global temperature is likely to increase an average of 3.2°C by 2100 [Raftery et al., 2017]. A specific science committee developed a joint bayesian hierarchical model to reveal that there is a 5% chance the earth increases in temperature less than 2°C by 2100 [Raftery et al., 2017]. It is agreed upon that the blame of the increase in temperature belongs to CO_2 amongst other gasses created by human activities [Osterkamp and Lachenbruch, 1990]. In Alaska specifically, the 20^{th} century reflects a increasing trend of 2 - 4° C of the permafrost [Osterkamp and Lachenbruch, 1990]. In 1990 climate models predicted a warming of the climate of about 3 - 6° C by the middle of the 21^{st} century in Alaska [Osterkamp and Lachenbruch, 1990]. The effects that will follow this dramatic temperature change will raise the average sea level, cause animals to migrate to new locations, threaten the population of animals that are sensitive to their climate conditions [Osterkamp and Lachenbruch, 1990, Adams-Hosking et al., 2011, Taylor, 2008]

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2.3 Population Modeling Using Ordinary Differential Equations

One of the simplest equations for modeling populations is the exponential growth ordinary differential equation (ODE), which is displayed below.

$$\frac{dN}{dt} = rN, \quad \text{where} \quad N(0) = N_0 \tag{2.1}$$

Consider $r = \text{Birth} - \text{Death}$, then r is a constant that represents the growth rate of the population at any given time. Also, N is the population at time, t. So, $\frac{dN}{dt}$ is the population rate of change that is dependent on time, t.

A more accurate way of describing population growth is using a logistic growth

ODE, which can be observed below.

$$\frac{dN}{dt} = rN\left(1 - \frac{N}{K}\right) \tag{2.2}$$

Now, r will still represent the growth rate of the population and K is the carry capacity. Most species follow a logistic growth pattern due to environmental constraints such as: area, food, and other essential resources. A great way to understand that K is the carry capacity is by graphing Equation(2.2).

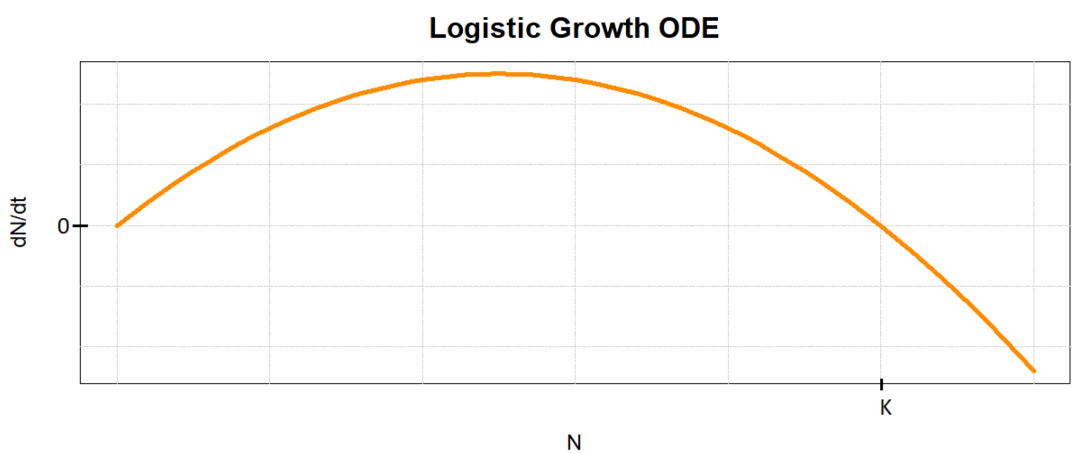

Figure 2.1: This figure illustrates when the population, N, is in the interval $(0,\ K)$, then it will continue to grow as t gets bigger. But, if N was larger than K, then the population would continue to get smaller as t get bigger.

So, by setting a carry capacity, K, to a value that represents the environmental limits, a more accurate representation of a specie's population can be analyzed.

By using the ordinary differential equations and adjusting the parameters, r and K, almost any population of a species can be modeled. Some species are dependent on other species to survive such as: bears and salmon. This is referred to as an interaction between two species. by using the Lotka-Volterra equation an interaction between two species can be modeled.

2.4 Lotka-Volterra Model

The Lotka-Volterra equation, which is also referred to as the predator-prey model, is constructed from two nonlinear ordinary differential equations as displayed below.

$$\begin{aligned} \frac{dx}{dt} &= \alpha x - \beta xy \\ \frac{dy}{dt} &= \delta xy - \gamma y \end{aligned} \tag{2.3}$$

Consider x as the prey, y as the predator, α, β, δ, and γ are positive real parameters that describe the interaction of the two species. Thus, leaving $\frac{dx}{dt}$ and $\frac{dy}{dt}$ as the instantaneous population growth rate of the two species. Based on Equation(2.3), the two species separately would be represented by the exponential ODE, Equation(2.1). The interaction term changes the exponential growth to an oscillation due to the dependency of at least one species.

Now, with Theodore Modis' research in logistic growth versus Lotka-Volterra, a predator-prey model can be constructed with logistic growth [Modis, 2011]. The logistic predator-prey model would have the following format.

$$\begin{aligned} \frac{dx}{dt} &= a_x X - b_x X^2 + c_{xy} XY \\ \frac{dy}{dt} &= a_y Y - b_y Y^2 + c_{yx} XY \end{aligned} \tag{2.4}$$

Where c_{xy} and c_{yx} are real numbers that describe the interaction of the two species. This model is describing two species who have an interaction with themselves, which is the logistic equation, and an interaction with each other, which is the interaction terms added at the end of each equation.

The fundamentals of each of these equations will be used in the construction of our model. The Lotka-Volterra will assist in the illustrating of interaction between species while the logistic equations will be used to describe the environmental limits of each species.

Chapter 3

Construction of Predator-Prey Model

3.1 Population Model of Alaskan Brown Bears

A few different articles attempt to reflect the Alaskan brown bear population growth or decay rate. According to [Barnes and Van Daele, 2010], the growth rate of the Alaskan brown bear population should yield 101.4%. Also, according to this study, the adult male survival rate is 81%, adult female is 89%, male sub adult is 56%, female sub adult is 89%. First, to clarify that in this article sub adults are 5 years old or younger while adults are the complement of this. Now, according to the Alaska Fish & Game Department, the current recorded population for brown bears is 30,000 [ADFG, 2021]. Since the proportions of each gender/age group was not stated in Van Daele's article, another was used to estimate the proportions [Wielgus and Bunnell, 1994]. Based on this assumption the proportions are: adult male is 30%, adult female is 22%, sub adult male 22%, subadult female is 11% and cubs are 15% [Wielgus and Bunnell, 1994]. Now, Barnes and van Daele included cubs as sub adult so cubs were split into 7.5% male and 7.5% female and added it to the sub adult categories.

The survival rates of each category changes from each article and soon, the average between them will calculated. While most are relatively the same, some differ a bit. When looking at [Barnes and Van Daele, 2010] survival rates we get: 85% for males, 93% for females, 56% sub males, and 89% sub females. Even van Daele and Barnes note the difference between each article they read and compared it to theirs. The harvest rate was said to be absorbed in the survival rates, so the inclusion of a separate rate for harvesting didn't seem necessary. Before jumping into the model the reproductive rate which was calculated as 42% cubs/female/year [Barnes and Van Daele, 2010]. Finally, the basic logistic growth model is presented below.

$$\frac{dN}{dt} = rN\left(1 - \frac{N}{K}\right) \tag{3.1}$$

Where r is the growth rate which is calculated by subtracting all the mortality rates with their respected gender/age group from the reproductive rate. N is the population of the Alaskan brown bears and K is the carrying capacity. The population shouldn't reach more than 40,000 to 50,000 due to environmental control, so it seems fair to keep the carry capacity around there [ADFG, 2021]. From the data collected by [Wielgus and Bunnell, 1994, Barnes and Van Daele, 2010] a graph below is produced.

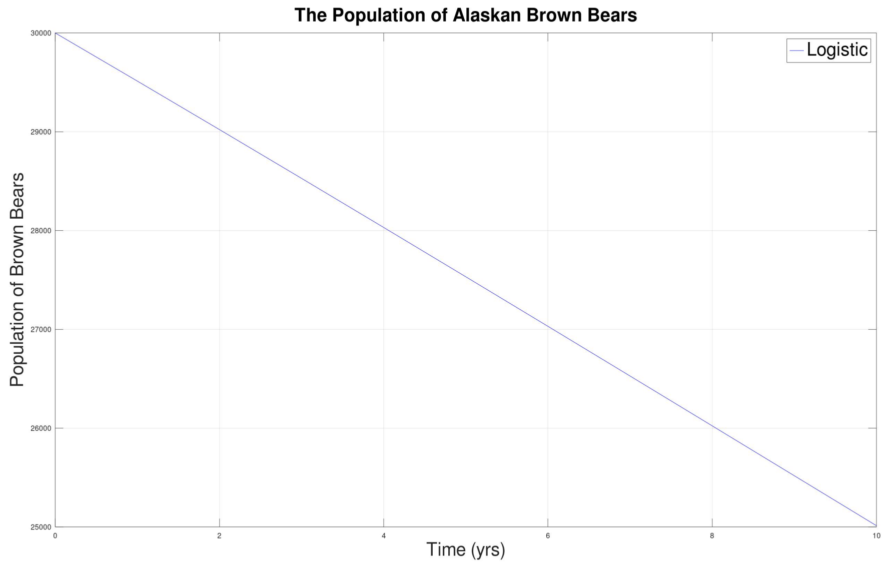

Figure 3.1: Using the combined data from the Van Daele's and Wielgus' articles, we can plot a prediction of the Alaskan brown bear population after 10 years[Barnes and Van Daele, 2010, Wielgus and Bunnell, 1994]. The population decreases by 16.63% over those 10 years.

From this graph we can see that the population is definitely decreasing over time. The end predicted population after 10 years is 25,012 which implies a 16.63% decrease in population over that time frame. While [Barnes and Van Daele, 2010] seemed to have predicted an increase in population, the construction of their model isn't available to compare against. Van Daele and Barnes did compare their result to other article and found similar results produce by the basic logistic growth model, Equation (3.1) [Barnes and Van Daele, 2010]. From Van Daele and Barnes discussion models ranged from about 16.6% increase over 10 years and a 19% decrease over 11 years[Barnes and Van Daele, 2010]. A reason for the difference in population growth could be the area the data was collected in.

When analyzing the [Wielgus and Bunnell, 1994] article there were some differences in survival rates that were worth exploring. The survival rate for adult males is 0.7, 0.93 for adult females, 0.89 for sub adult males, sub adult females is between 0.89 and 0.93, which averages to be 0.91, and lastly cubs were 0.78 [Wielgus and Bunnell, 1994]. The reproductive rate for the brown bears was stated to be 0.46 [Wielgus and Bunnell, 1994]. Using the same idea as the model above but with the new survival and reproductive rates the graph below is produced.

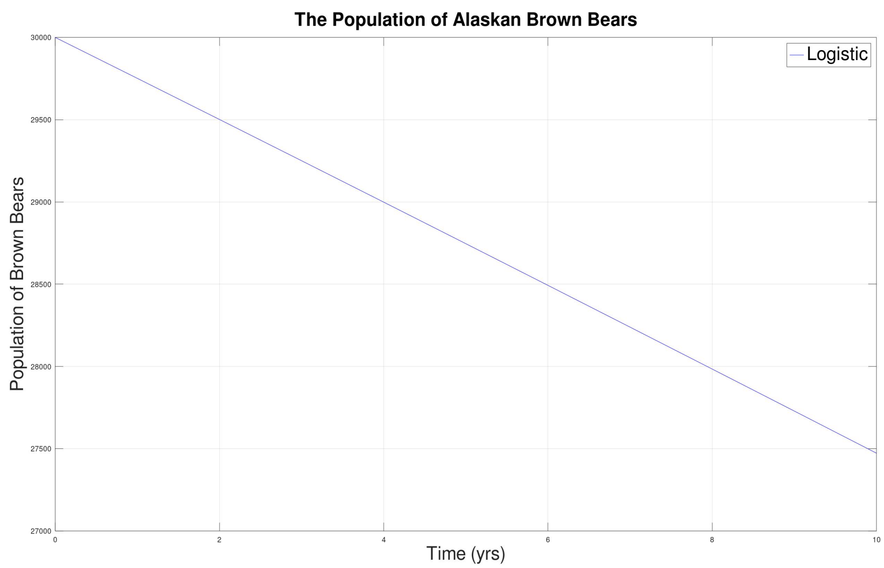

Figure 3.2: The population seems to be decaying less than the Van Daele and Barnes model with a population decrease of about 8.42% over 10 years.

The population of the Alaskan brown bears is still decaying over time but not as much as the Van Daele model. As discussed earlier the decline of about 8.42% over 10 years still makes sense when comparing to the other models Van Daele mentioned [Barnes and Van Daele, 2010]. Van Daele and Barnes' data was collected from Kodiak Island while Wieglus and Bennell's was collected in southwestern Alberta, Canada [Barnes and Van Daele, 2010, Wielgus and Bunnell, 1994].

Another study that was compared to a lot by Van Daele was McLellan's 1989 publication [Barnes and Van Daele, 2010]. Again, noticing different survival and reproduction rates while also not mentioning much about the gender/age proportions of the bears. Also, McLellan's data was collect about grizzly bears in southeastern British Columbia which is a subcategory of the brown bear species [McLellan, 1989]. McLellan's article gives 2 sets of survival and reproductive rates. The first being from the Flathead Valley and the second being the altered data to receive 0.0 rate of increase [McLellan, 1989]. The Flathead Valley survival rates can be found on table 2 of [McLellan, 1989] which produced 82% for adult males and females, 94% for sub adult males and female, and an average of 85% for cubs. The reproductive rate was calculated to be 421% from table 2 as well [McLellan, 1989]. The results of the Flathead Valley produces the graph below.

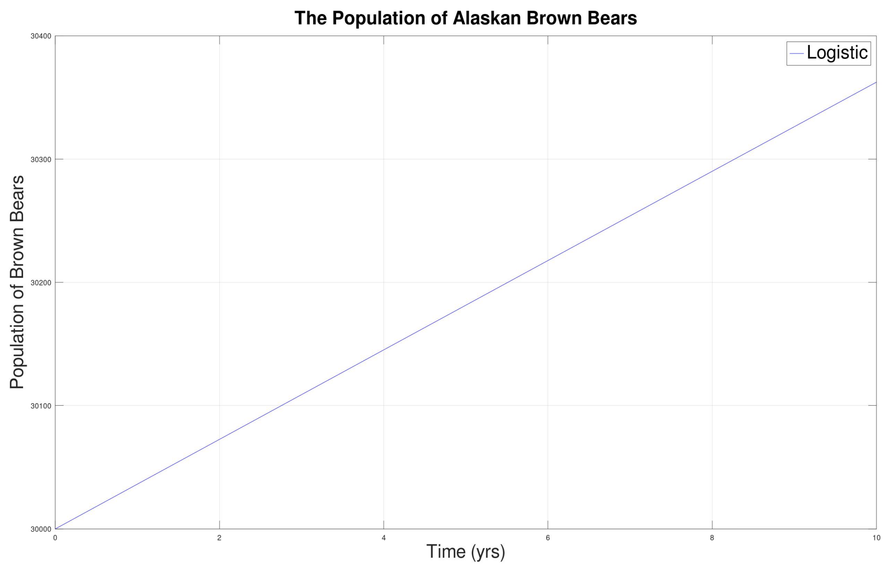

Figure 3.3: The increase in population from this models is very minimal and is about a 1.12% increase over 10 years. This graph represents the Flathead Valley in British Columbia.

The Flathead Valley model predicts that over a span of 10 years the population will increase by 1.12% which is not much. Based on the other models, it seems safe to conclude that location makes a big difference on the determining the outcome of the brown bear population. Also, as discussed earlier, McLellan has another set of survival and reproductive rates that they adjusted to estimate a 0 rate of increase [McLellan, 1989]. The survival rates are: 76% for adults, 69% for sub adults, and 33% for cubs. The reproductive rate is 85% [McLellan, 1989]. This is the highest reproductive rate in any of the articles and also some of the lowest survival rates too.

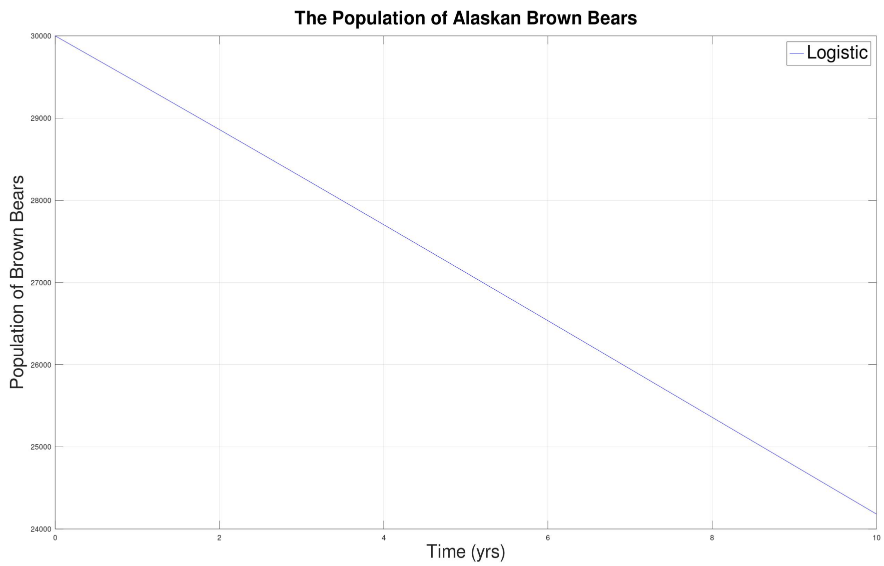

Figure 3.4: With this new model there is a decrease in population of 19.40% over 10 years.

McLellan altered the data in table 2 of his article [McLellan, 1989], so the inclusion of this data in the averages of survival and reproductive rates for the model would seem to be inappropriate, therefore should be left out. The intent of McLellan was said to create a rate increase of 0% [McLellan, 1989]. Looking at the graph above it does not appear to be stable so it is unclear how McLellan designed his model, but possibly by using different gender/age proportions. When reading the article, information on the gender or age proportions of the brown bears in Flathead Valley didn't seem to appear.

Now, if we collect the average survival and reproductive rate between the three articles [Barnes and Van Daele, 2010, Wielgus and Bunnell, 1994, McLellan, 1989], then this should give us a better interpretation of Alaskan brown bear growth rate.

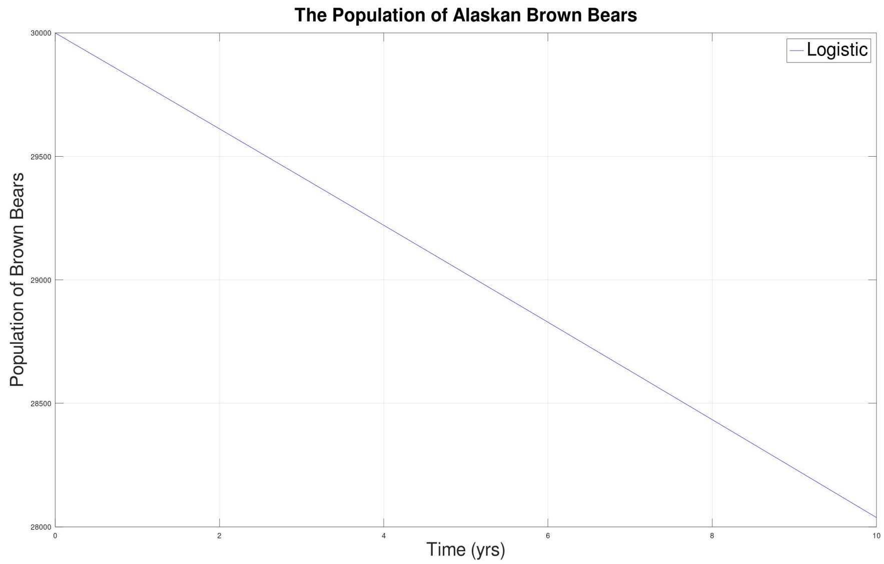

Figure 3.5: Looking at this model we get an end result of 28,038 brown bears after 10 years which implies a 6.54% decrease in population.

The average survival rates are: 79% for adult males, 89.33% for adult females, 79.67% for sub adult males, 91.33% for sub adult females, and 87.67% for cubs. Also, the average reproductive rate is 43.37%. Inserting this into the model above we get the graph below. The population of brown bears in Alaska appears to decreasing slowly over time. The average harvest rate in Alaska right now is about 5% [Becker and Crowley, 2021]. Others have also estimated the harvest rate to be $6.7 - 10\%$ [Barnes and Van Daele, 2010]. So, the harvest rate is know to fluctuate. The Alaskan fish and game department can adjust the harvest rate to gradually increase or decrease the population. Since the growth rate is $r = -.016123$, if the fish and game department decided to lower the number of brown bears harvest each year by a couple percent then population would start to gradually increase. By adjusting the harvest rate every few years the Alaskan government is able to create a stable population for the brown bears.

3.2 Population Model of Salmon

The life cycle of pacific salmon *Oncorhynchus* in Alaska is quite interesting. They begin their journey hatching in streams and making their way down to the ocean. At this point they spend between 1 to 7 years out at sea before returning back to the place where they came from. They will then travel several miles upstream where they can spawn. They use a lot of their energy reaching an optimal place to lay and fertilizing their eggs, so much so that once they are done with this process, they usually die shortly after. Pacific salmon lay between 1,500 to 10,000 eggs when spawning, but only 0 to 10 of these eggs will reach adulthood [Scientist, 2022].

When looking at the rate at which salmon reproduce, it appears to be exponential. If on average for every salmon that lays eggs, 5 of their offspring will be able to make their way back to repeat the process. Using this idea, the below exponential function is generated.

$$F(t) = F_0(5^t) \tag{3.2}$$

Where F_0 is the initial number of salmon that laid laid eggs and t represents time in years.

$$F(t) = F_0 e^{rt} \tag{3.3}$$

Where $r = \ln 5$, and represents the reproductive rate. Now, taking the derivative of this $F(t)$ will provide the salmon population rate of change.

$$\frac{dF}{dt} = rF_0 e^{rt} = rF \tag{3.4}$$

The above first order ordinary differential equation can be used in the predator-prey model, but to examine the results of it's behavior, Equation 3.3 could provide a better insight of the population trend of salmon. So, below is a plot that illustrates the growth of the salmon population with an initial starting point of 20.

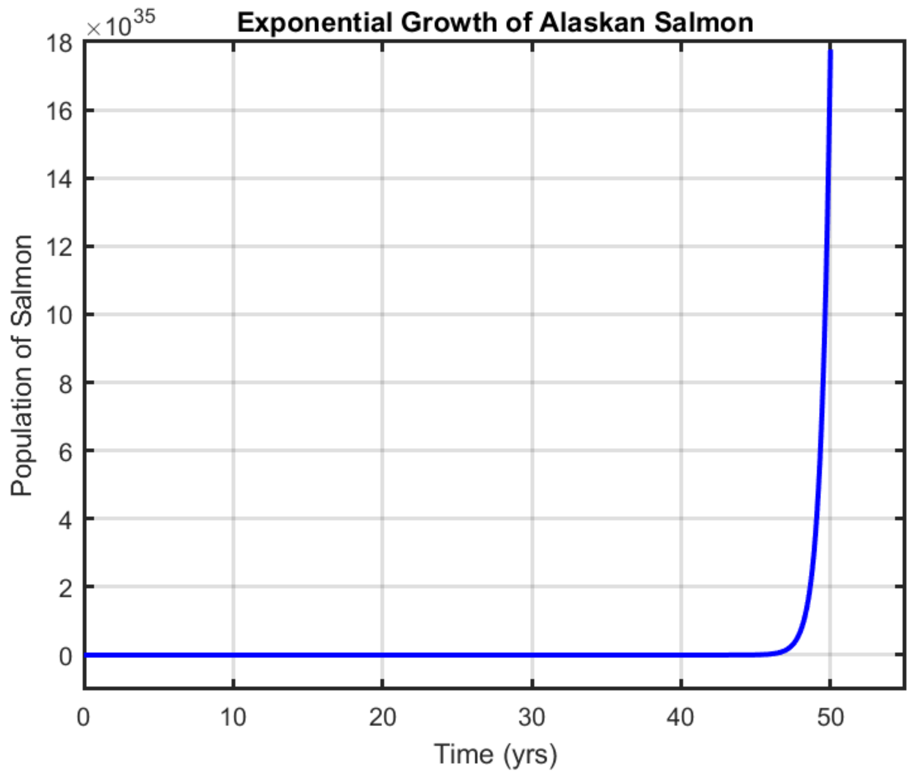

Figure 3.6: The plot above illustrates the population of salmon increasing exponentially resulting in a total of approximately 1.8×10^{36} salmon after 50 years.

Judging from the figure above the population appears quite small until around year 47. The population at the 47 year mark is approximately 5.7×10^{32} salmon which is not small at all. To see this trend a little bit better the graph below is the same plot but for 2 years instead of 50.

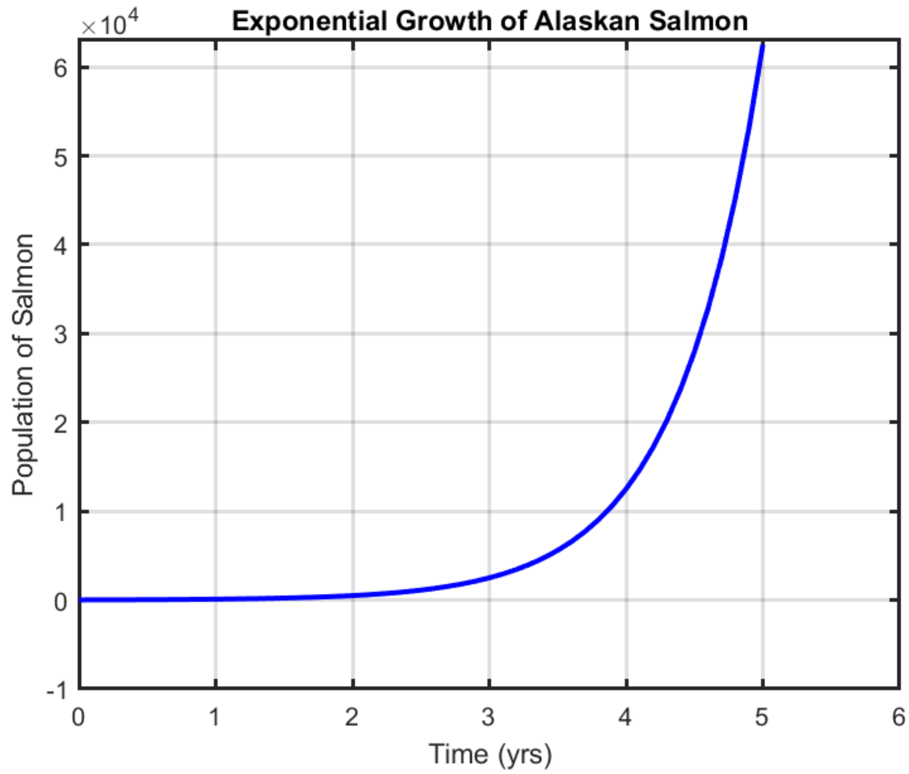

Figure 3.7: The population of salmon quickly moves into the tens of thousands just under 4 years.

The growth rate is a bit easier to see in this plot than Figure 3.6. In just 4 years the population of salmon increases from 20 to 12,500 and 1 year after this the population grows to 62,507 which is a growth of 50,006 salmon. As Figure 3.6 shows, the population gets extremely large in a short period of time. There is an environmental limit to the number of salmon that can come back to spawn in these streams.

There was a dramatic increase in the number of sockeye salmon *Oncorhynchus nerka* returning to Bristol Bay in 2021 compared to any of the previous years, but the average weight of sockeye salmon during this year decreased by a pound compared to the average of the past 20 years [Elison et al., 2022]. In Bristol Bay, there are 5 different species of salmon: sockeye *O. nerka*, chinook *O. tshawytscha*, coho *O. kisutch*, chum *O. keta*, pink *O. gorbuscha* [Elison et al., 2022]. The sockeye species make up a large majority of the inshore runs[1], harvests[2], and escapements[3] in Bristol Bay each year, which makes them the most valuable when estimating the carry capacity [Elison et al., 2022].

Sockeye Comparison Between Weight and Run Size in Bristol Bay

Year	**Weight (lbs)**	**Run (mil)**
2001	6.7	22.3
2002	6.1	16.9
2003	6.3	24.9
2004	5.8	41.9
⋮	⋮	⋮
2017	5.5	57.6
2018	5.1	63.0
2019	5.1	56.4
2020	5.1	58.3
2021	4.7	67.7

Table 3.1: This table gives a brief look at the correlation between run size and the average annual weight of sockeye salmon in Bristol Bay. The complete data can be seen in Table B.1 in Appendix B.

[1]Inshore runs are when salmon migrate back from the sea to spawn.

[2]Harvests are the number of fisheries gathered by commercial fisheries.

[3]Escapements are salmon that escape the fisheries and continues up stream to spawn.

In the first 3 years of this table the weight seems to be dramatically higher than the last 3 years, but the opposite effect appears in run size. This proposes the question that there might be a correlation between the run size and average weight of salmon each year. When taking a closer look at Table B.1 in Appendix B the trend becomes more apparent when comparing the sockeye's run size and average annual weight. Before calculating the correlation between these two events, a plot must be analyzed to see if the trend is linear.

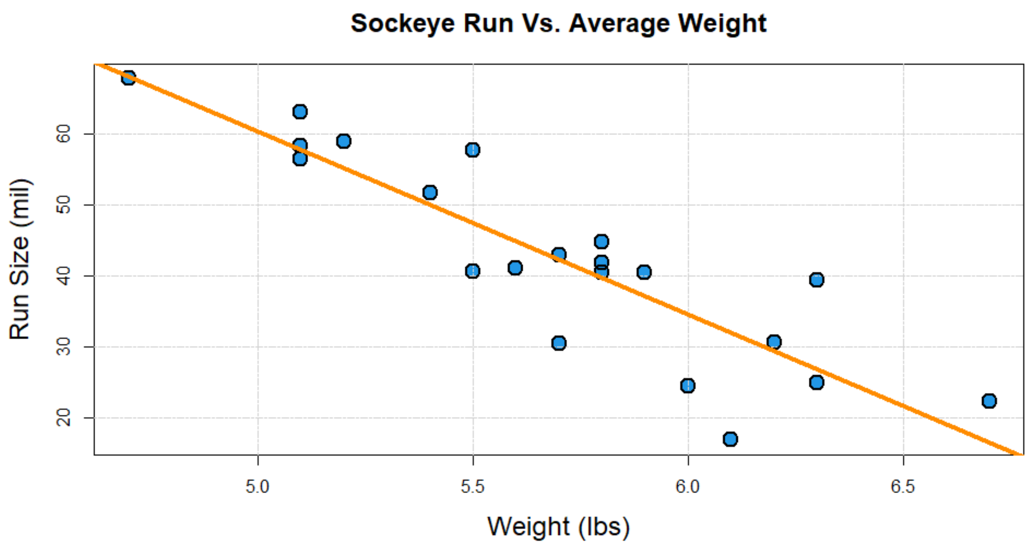

Figure 3.8: The run size of the sockeye salmon decreases as the their average weight increases. Since there are multiple variables that make up the size of a salmon run each year, this helps explain the variance seen in the plot.

Based on the figure above, there does seem to be a linear correlation between sockeye run size and average weight. So, calculating the correlation of these two events gives a value of -0.88. Since the correlation of these events are strong, an environmental limit of salmon can be estimated based on the maximum annual volume of sockeye salmon for the past 21 years. When looking at Table B.2 in

Appendix B, the maximum volume for a given run for the last 21 years is 7.34 million cubic feet (MMCF) in 2018. The average weight of sockeye salmon during this year was 5.1 lbs which is 0.4 lbs more than the lowest average weight of 4.7 lbs in 2021. Now, a carry capacity for sockeye salmon can be estimated by using the maximum volume and lowest average weight which produces a value of 68.4 million sockeye salmon. Sockeye are not the only salmon in the streams, but according to Table B.3 in Appendix B, they make up approximately 94% of the average annual commercial harvest in Bristol Bay. Implying that the run proportions are the same as the average annual commercial harvest, the value, 72.8 million, becomes the carry capacity for inshore salmon runs in Bristol Bay. According to the National Park Service (NPS), only $25-40\%$ of salmon who migrate back to Bristol Bay make it back to spawn while the others are harvested by commercial fisheries [NPS, 2020]. This now leaves the carry capacity to be 29.1 million salmon each year.

Now that a carry capacity of the salmon population has been approximated, the model can be rewritten as a logistic growth model as shown below:

$$F(t) = \frac{K}{1 + be^{-rt}} \tag{3.5}$$

Where $K = 29,100,000$ is the carry capacity, r is the reproductive rate, b is a constant, and t is time (yrs). Remember that we estimated $r = \ln 5$, but according to the NPS, only $25-40\%$ of these will make it back to spawn and reproduce. Thus, $r = 0.32 * \ln 5 \approx 0.515$, where 0.32 is the average of $25-40\%$. Then, taking the derivative of $F(t)$ with respect to time, t provides the below differential equation:

$$\frac{dF}{dt} = rF\left(1 - \frac{F}{K}\right) \tag{3.6}$$

Following this model, is designing a reproductive rate function, $R(T)$, that will be dependent on temperature, T. This will help simulate the effect of climate change on the reproduction of salmon, which is a main food source of the brown bear species.

3.3 Reproductive Rate Function of Temperature

Salmon have an optimal temperature range for the rate at which they grow. If the temperature of their environment goes outside that range, then salmon may change their location of spawning, or time in which they spawn [Weber Scannell, 1992]. If they do not take either of those options then they may fatigue and die before reaching the spawning location [Weber Scannell, 1992, ADFG, 2022]. So, when temperatures reach a critical point, mortality rates increase significantly, which consequently decreases their reproductive rate [Weber Scannell, 1992]. The idea for this section is to use salmon's mortality rate at different temperatures to approximate a reproduction function, $R(T)$, that is dependent upon temperature. While there is little research that scientifically describe the effects of salmon reproduction at each individual point in temperature, there are reports that estimate the optimum temperature range as well as critical points. Dr. Phyllis Weber Scannell wrote an amazing article in 1992 for the ADFG about the optimal temperature ranges for cold water fishes. In this article, she highlights the optimal range as well as the critical high temperature of sockeye salmon in Alaska [Weber Scannell, 1992]. Also, Katherine Carter has published an article that suggests temperatures below 2°C will result in high mortality [Carter, 2005].

Optimal Temperature Range For Pacific Sockeye Salmon

Species	Optimal (°C)	Low (°C)	High (°C)
Sockeye	$11 - 14$	< 2	> 22.2

Table 3.2: The optimal and critical high and low temperature range for sockeye salmon species in Alaska [Weber Scannell, 1992, Carter, 2005]. When salmon reach the location where they want to lay their eggs, the optimal temperature range differs and is often lower because of the need to save their energy.

As Dr. Scannel's report states, each researcher estimates slightly different temperature ranges due to a multitude of variables such as: acclimation, age, size, genetic strain, and physiological conditions of the fish [Weber Scannell, 1992]. That being said, we will be using Table 3.2 to help fit a curve that best illustrates the impact of temperature on the reproduction of salmon. Now, Katherine Carter's article explains that at these critical points the population would have a 50% mortality rate [Carter, 2005]. So, implying that under ideal conditions and optimal temperatures, 100% of the salmon population would survive the spawning migration to reproduce, and at the critical temperatures only 50% would survive. From Table 3.2 the optimal temperature range is $11 - 14$°C and the critical temperature points are at 2°C and 22.2°C, which can be observed on the graph below.

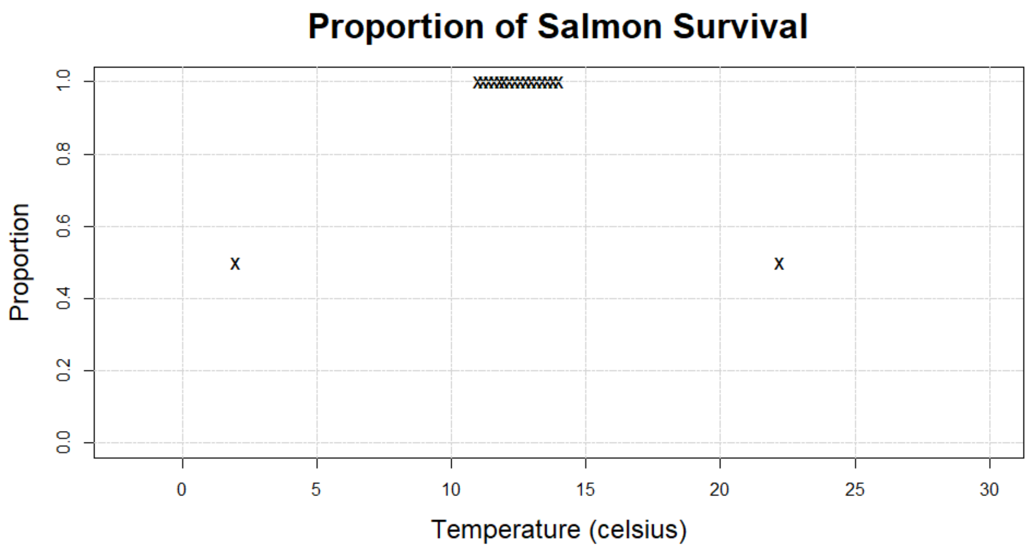

Figure 3.9: This plot shows the survival rate at the optimal temperature range and the critical temperature points based on Table 3.2.

Given that the optimal range is rather large, developing a function to approximate these data points will be rather difficult. The reproduction rate cannot drop below 0, which implies that we should be looking at a function displayed below.

$$R(T) = \frac{1}{1 + c(T - T_{opt})^2} \tag{3.7}$$

Where T_{opt} is the average of the optimal temperature range 12.5°C. T will represent temperature in Celsius and c is a constant that will be calculated to stretch the function horizontally as shown below.

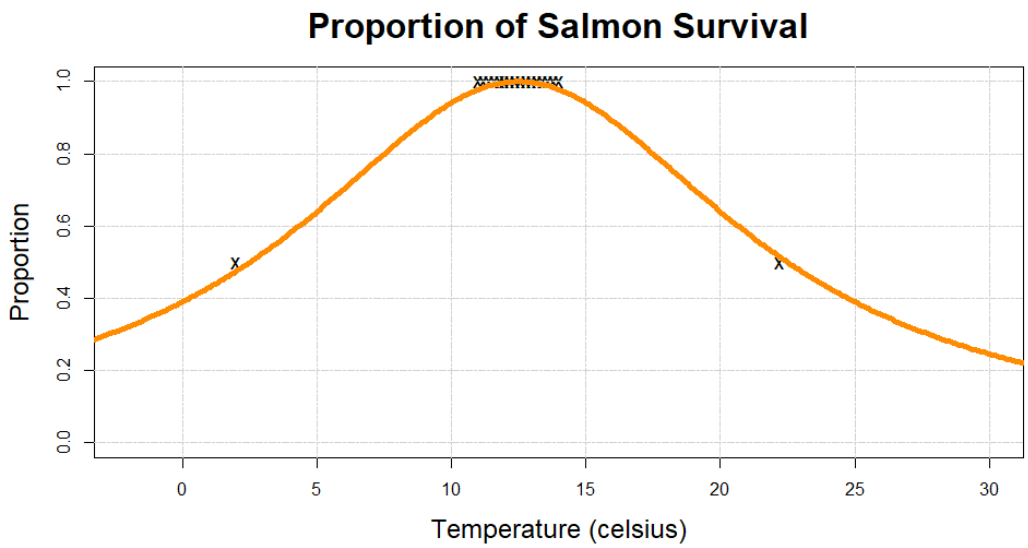

Figure 3.10: This figure represents the data estimated using Equation (3.7) where $c = 0.01$.

The main issue with using Equation (3.7) is the optimal range could be better represented by changing the power of 2 in the denominator to a power of 4, which will widen the curve while maintaining a steep decent as the temperature escapes the optimal region. Currently at the limits of the optimal temperature range the survival proportions are 0.978, which according to the article mentioned earlier should be closer to 1. The below equation fixes this issue by introducing the denominator being to the power of 4 instead of 2.

$$R(T) = \frac{1}{1 + c(T - T_{opt})^4} \tag{3.8}$$

Where $c = 0.0001$ in order to control the spread of the curve.

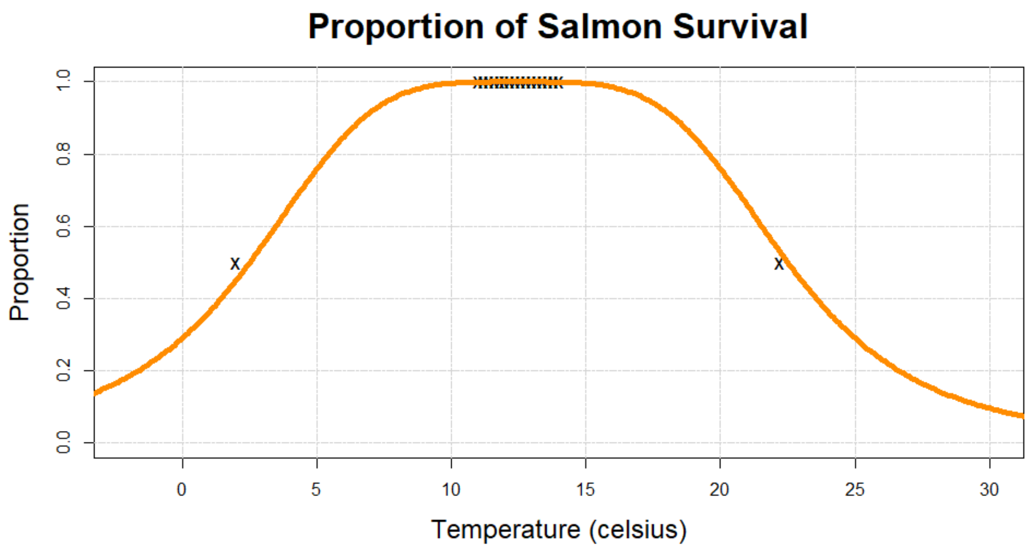

Figure 3.11: This figure represents the data estimated using Equation (3.8) where $c = 0.0001$.

This is a better fit for the optimal temperature range because the survival proportions are now really close close to 1. At the limits of the optimal range the survival proportions are 0.9995, which is approximately 1. During the salmon migration of 2004, Weaver Creek sockeye salmon experience a drastic rise in water temperature, which resulted in a higher than usually mortality rate [Farrell et al., 2008]. According to Anthony P. Farrell, temperatures were around 20.4°C and that 30% of the salmon population did not make it to the spawning location due to the excessive heat [Farrell et al., 2008]. Now, using Equation (3.8), and letting $T = 20.4$ we get $R(20.4) = 0.7197$. This means the we estimate approximately a 72% survival rate for the salmon migrating to their spawning locations. This also reveals a mortality rate of approximately 28% which close to Anthony P. Farrell's estimation.

So far, this reproduction function has just been estimating the proportion of salmon that would reproduce for the next iteration. Looking back at Equation (3.5), the reproduction rate, r, was when temperatures were ideal, or in the optimal range, so by taking the product of r and $R(T)$, we will have the final reproduction function as shown below.

$$R(T) = rR(T) = \frac{r}{1 + c(T - T_{opt})^4} \tag{3.9}$$

Where $c = 0.0001$, $T_{opt} = 12.5$, and $r = 0.32 \ln 5$. Lastly, we will replace the reproduction rate, r with the reproduction function, $R(T)$, in Equation (3.6).

$$\frac{dF}{dt} = R(T)F\left(1 - \frac{F}{K}\right) \tag{3.10}$$

To see the affect of temperature on the salmon population, we will compare Equation (3.10) at different temperatures.

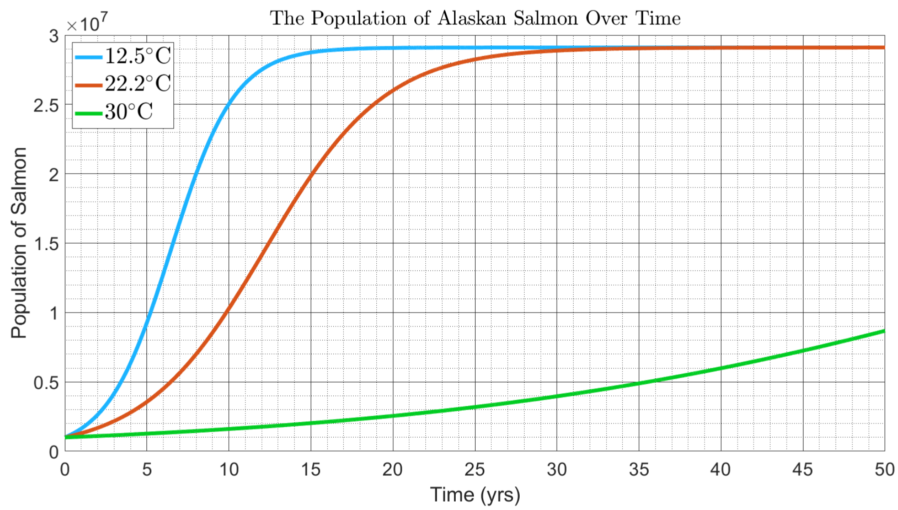

Figure 3.12: These three curves represent the outcome of the reproduction function, Equation (3.9). The initial population was set to 1,000,000 and the parameters discussed in Equation (3.5), (3.6), & (3.8) were used in the production of these plots.

At the optimal temperature, $T = 12.5°C$, the population grows drastically from 1 million to almost 29.1 million in 20 years as seen in the top graph. As the temperature moves further away from the optimal temperature, the reproduction of salmon is negatively affected, resulting in a slower growth rate, which can be observed in the middle and bottom graph. Notice, that as the temperature becomes drastically far away from the optimal temperature, the growth rate slows down significantly. By setting the $T = 30°\text{C}$, the salmon population takes nearly 200 years to reach their environmental carry capacity.

By replacing the reproduction rate of salmon with a function dependent upon temperature, we can see the drastic affects on the salmon population as temperature changes. If we estimate, or predict, how temperature will change with respect to time, then we can apply it to the salmon population model and discuss the change in growth rate over time due to temperature changing at the same time. In the next section we will discuss the growth of temperature over time and create a function that will predict temperature at any point in time. Then, we will incorporate our new function into our reproduction function, Equation (3.8), to explore the affects on the salmon population.

3.4 Sea Temperatures In Alaska

The global temperature of the earth has been growing exponentially over the past 100 years [Crowley, 2000]. Temperatures are expected to keep growing faster for at least the next 30 years [UA, 2016], unless changes are made now to the output of greenhouse gas emissions [UCAR, 2022]. Below is a graph illustrating the annual deviation of global surface temperature from the 20^{th} century average of 13.9°C.

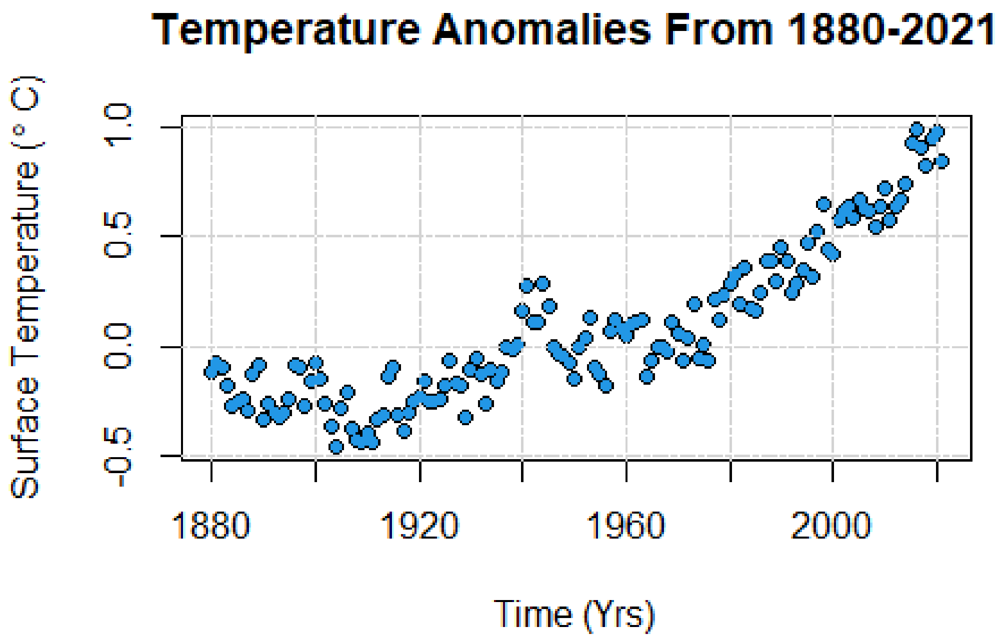

Figure 3.13: This data comes from the National Oceanic and Atmospheric Administration (NOAA) [NOAA, 2022]. The data appears to have an exponential or even a quadratic trend.

Any of the points below 0°C represent the years in which the temperatures were less than 13.9°C and the points above 0°C represent years were the temperatures were greater than 13.9°C. Judging from the plot above there seems to be a little sense of slowing down after 2010 which aligns with statements made by the EPA saying there has been a recent reduction in the emissions of carbon dioxide [EPA, 2019]. The graph above shows that the earth's temperature decreases from 1880 till about 1910 before increasing almost exponentially to the present. Starting around 1970 to the present the data appears to have linear growth. While an exponential regression model can be used to fit the data, a quadratic model would seem to work better because of the initial decrease from 1880 to 1910. The quadratic model would look like:

$$T(t) = at^2 + bt + c \tag{3.11}$$

Where $a = 7.95 * 10^{-5}$, $b = -30.25 * 10^{-2}$, and $c = 287.57$. The change in surface temperature, $T(t)$, over time, t, looks like:

$$\frac{dT}{dt} = 2at + b \tag{3.12}$$

Function T seems to fit the data well given the graph below.

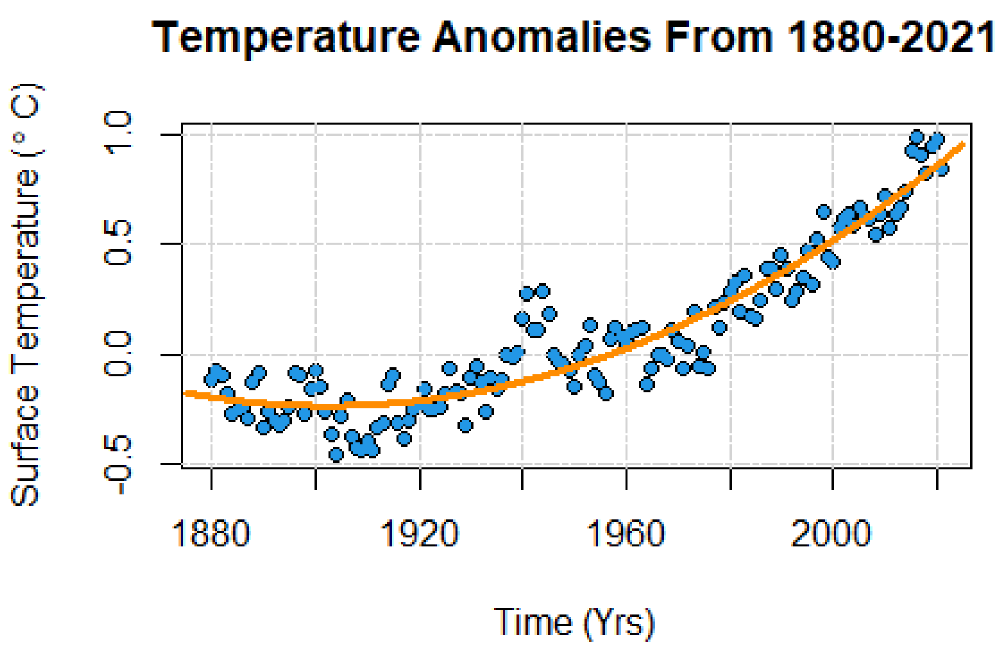

Figure 3.14: Figure 3.13 was fitted with the quadratic function $T(t)$. The data appears to have a linear growth starting after 1970.

There is a possible issue that should be explored before continuing. This model projects the change in global temperatures of the earth, but salmon live in the ocean.

So, designing a model to fit the earth's temperature might not accurately reflect the environmental temperatures of this species. Luckily the National Oceanic and Atmospheric Administration also has data on the global sea surface temperature over the same time period. Below is a graph looking at the global sea surface temperature anomalies with respect to the 20^{th} century average of 13.9°C.

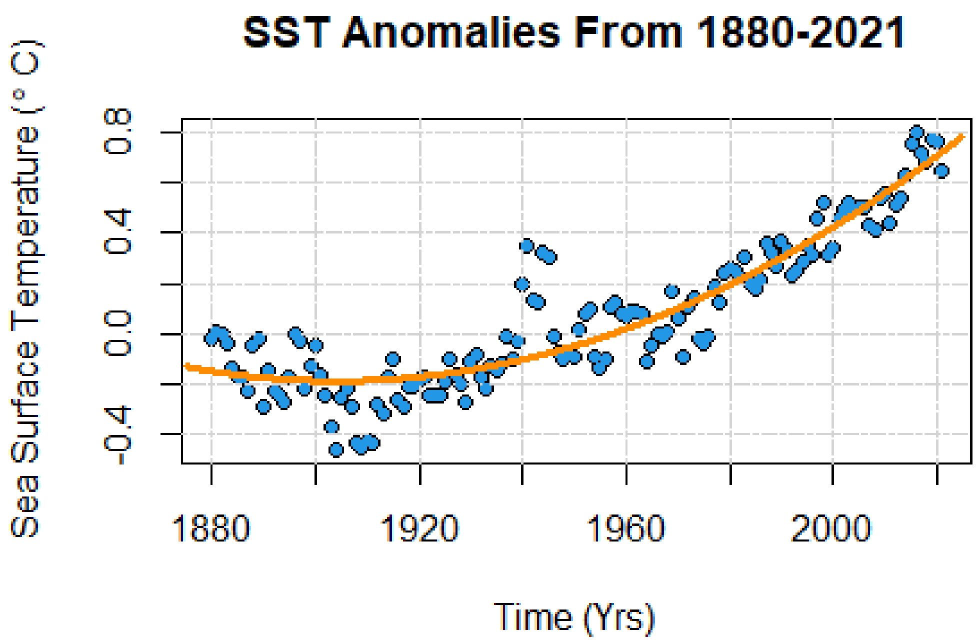

Figure 3.15: This is data was fitted with and exponential model using data from the NOAA [NOAA, 2022].

Since the graph above has a similar trend to Figure 3.13, a quadratic model seemed to fit this data well. The new parameters for the quadratic model are, $a = 6.67 * 10^{-5},\ b = -0.25,$ and $c = 241.53.$

Looking at the data and Figure 3.15 after 1970 the trend begins to appear linear which means the quadratic model doesn't seem to fit the data as well. Because of this, it might be more important to only look at SST, sea surface temperatures, after 1970. Also, Alaska is ranked 40^{th} in the nation with total greenhouse gas emissions, which may effect that region's SST trend differently then other regions that may have a larger effect on the national average [ADEC, 2018].

Alaska is littered with river streams, but salmon can be seen predominately in the south parts of Alaska, such as Anchorage, Kenai peninsula, near Juneau, and Alaska Peninsula [ADFG, 2021]. According to the Alaska Fish and Game Department, salmon can be seen in these streams from June to September [ADFG, 2021]. For this reason, water temperatures in these regions and during these months will be sampled to model the change in temperature over time. With these new observations in consideration the plot below is produced.

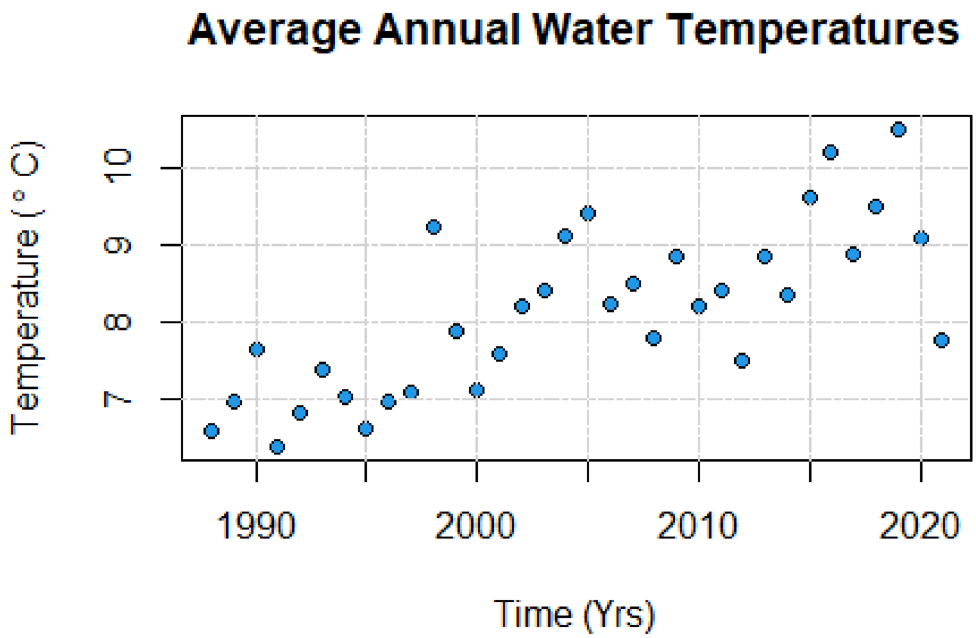

Figure 3.16: The source of the data used to produce this plot was the USGS current water data for Alaska [USGS, 2022]. Each data point is the average temperature for each year during June to September.

Viewing the graph above, a linear regression model would fit well. When using the USGS database, there were plenty of streams where the Alaskan government was collecting data. There were a few issues when looking at the data sets for each stream. First, most data sets were a small duration of a few years, so that wasn't enough time to model a trend. Second, some data sets were missing data for a couple months every year or even just had big gaps for several years. In the end, only 5 data sets were usable for analyzing trend over time. The 5 streams used for this analysis are Cooper Creek on the Kenai Peninsula, Kenai River at Cooper Landing, Russell Creek on the Alaska Peninsula, Terror River, just south of the

Alaska Peninsula, and Staney Creek which is south of Juneau. Below are the plots of each stream fitted with a model that closely represents their trend.

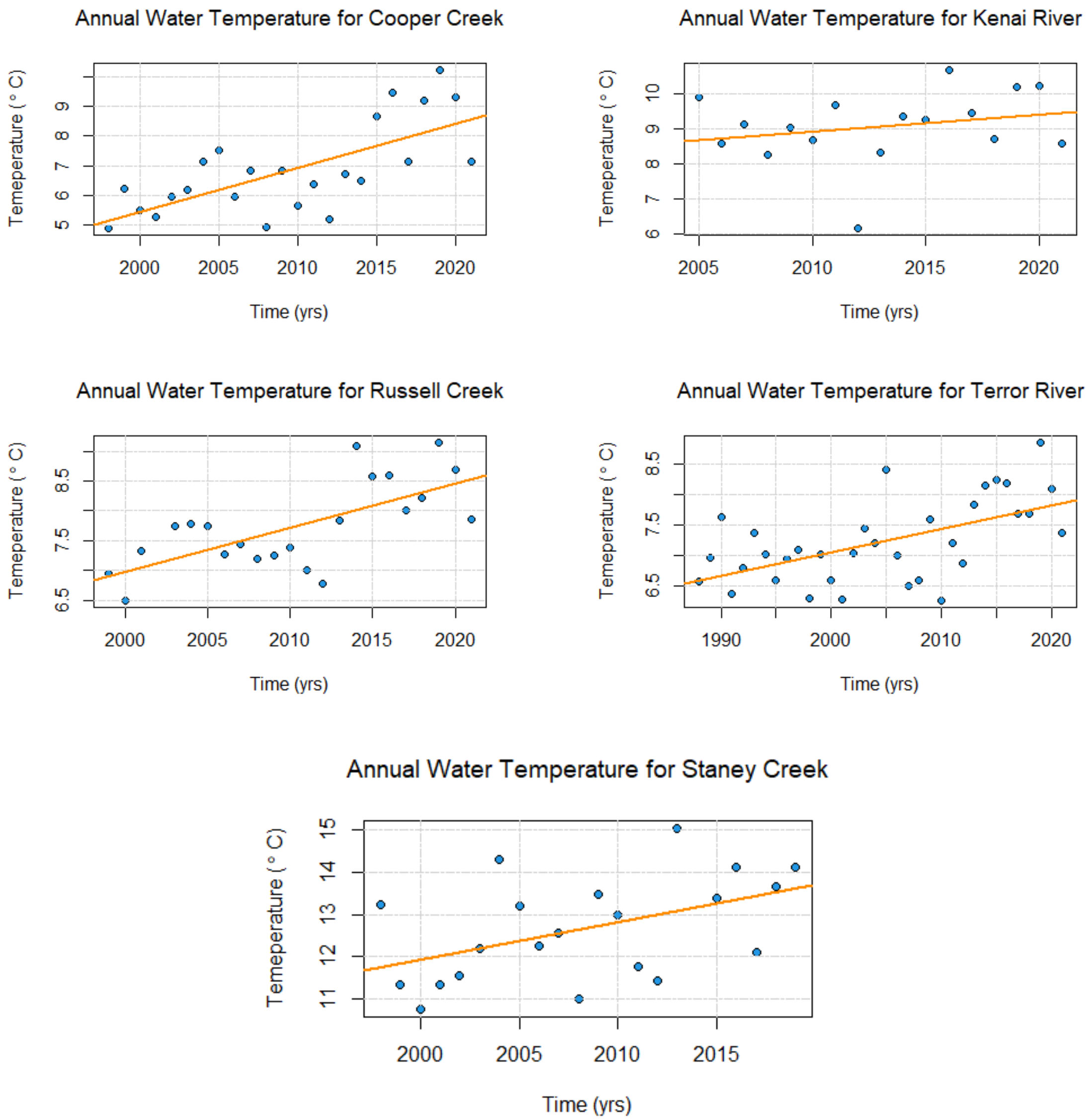

Figure 3.17: These are the water temperature trends for each river fitted with linear models.

Each of these plots follow closely to either a linear or sinusoidal trend. The mean of their slopes is 0.0797 °C per year. When fitting a linear model to Figure 3.16 the point estimate, or slope appears as 0.0803 °C per year, as shown below.

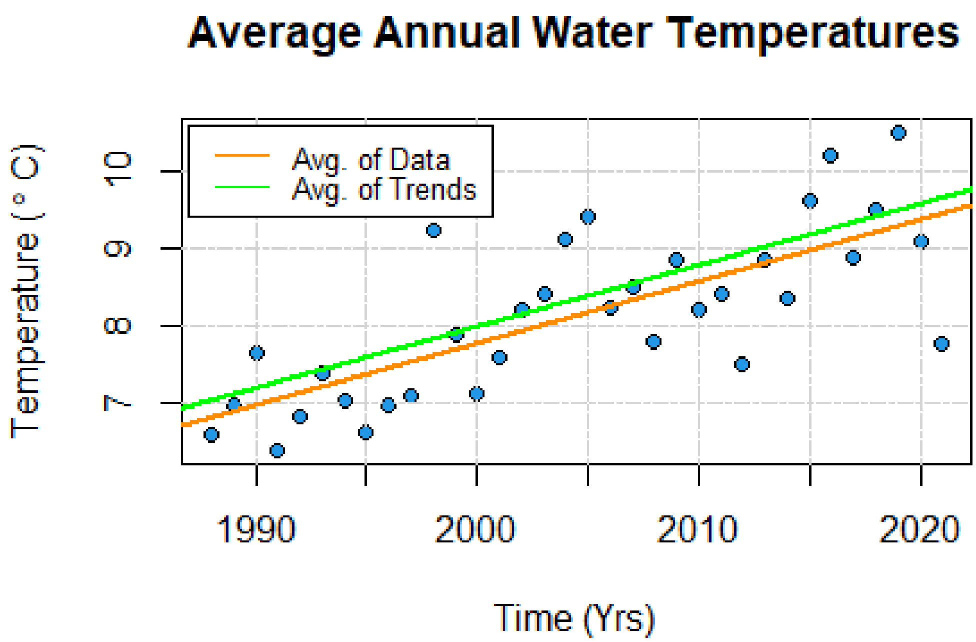

Figure 3.18: The orange line represents the trend of the average water temperature in Alaska for the past 33 years. The green line represents the average trend for each stream that was sampled in Alaska.

These lines are similar to each other, but do have slight differences. They seem to be parallel which implies that the average growth for each stream is the same as the change in the average annual temperature of all the streams over time. The difference in intercept has to do with each stream having different temperatures during each period of time. Looking back at Figure 3.17, around the year 2000 the Staney Creek has temperature of about 11 °C while Russell Creek, Terror River, and Cooper Creek were around 6 to 7 °C. This could be the result of Staney Creek being further south than the other streams where places are warmer. The important part of this is that for the past 33 years the change in Alaskan water temperature during the months in which salmon migrate from the ocean to freshwater to spawn has a linear growth of 0.08 °C per year. The model for the change in water temperature in Alaska can now be represented as:

$$T(t) = r_T * t + b_T \tag{3.13}$$

With $r_T = 0.08$ and $b_T = -152.9$. r_T represents the average growth of temperature over time as seen reflected for the past 30 years, b_T represents the initial temperature of the water in Alaska about 2000 years ago, and t represents the time in years with the initial staring point 0 B.C. Obviously the average temperature of Alaskan rivers and creeks 2000 years ago was not -152.9 °C, so this linear regression model is only useful for short time periods which makes sense when considering how difficult it is for meteorologists to confidently predict the weather for the next 40 years [UA, 2016].

By adjusting b_T, the starting time of the model will change. The initial starting point of this model should be the present since the predator-prey model being constructed will be reflective of the present conditions. So, letting $b_T = 9.54$ changes the initial starting time to the present year, 2022. This completes the Alaskan water temperature model and can now be added to the predator-prey model for analysis.

3.5 The Final Model

With all the individual components of the model constructed, it is time to piece them all together, while adding an interactive component. As a reminder the equation for the Alaskan brown bear species, Equation (3.1), is displayed below.

$$\frac{dN}{dt} = rN\left(1 - \frac{N}{K_N}\right)$$

Now, the equation for the salmon species and its function components, Equation (3.6), (3.8), (3.13), are shown below.

$$\frac{dF}{dt} = R(T)F\left(1 - \frac{F}{K_F}\right)$$

$$R(T) = \frac{r_F}{1 + c(T - T_{opt})^4}$$

$$T(t) = r_T t + b_T$$

These are two logistic growth models and are currently independent of each other. To include interaction between the two species, we will be using Theodore Modis' model, Equation (2.4), for inspiration.

$$\begin{aligned} \frac{dF}{dt} &= R(T)F\left(1 - \frac{F}{K_F}\right) - c_{FN}FN \\ \frac{dN}{dt} &= rN\left(1 - \frac{N}{K_N}\right) + c_{NF}FN \end{aligned} \tag{3.14}$$

Where $c_{FN}FN$ and $c_{NF}FN$ are the interaction term that. With the model created, performing an analysis can help identify equilibrium points as well as determine outcomes of certain initial conditions.

Chapter 4

Analysis of Model

Chapter 5

Results

Chapter 6

Discussion

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Appendices

Appendix A

BROWN BEARS

Appendix B

SALMON

Sockeye Comparison Between Weight and Run Size in Bristol Bay

Table B.1: Comparing the average weight of sockeye salmon to their run size in Bristol Bay each year. The data used to make this table was taken from the "*2021 BRISTOL BAY AREA ANNUAL MANAGEMENT REPORT*" [Elison et al., 2022].

Year	**Weight (lbs)**	**Run (mil)**
2001	6.7	22.3
2002	6.1	16.9
2003	6.3	24.9
2004	5.8	41.9
2005	6.3	39.3
2006	5.7	42.9
2007	5.8	44.8
2008	5.8	40.4
2009	5.9	40.4
2010	5.5	40.6
2011	6.2	30.6
2012	5.7	30.4
2013	6.0	24.4
2014	5.6	41.1
2015	5.2	58.8
2016	5.4	51.7
2017	5.5	57.6

Continued on next page

Table B.1 – continued from previous page		
Year	**Weight (lbs)**	**Run**
2018	5.1	63.0
2019	5.1	56.4
2020	5.1	58.3
2021	4.7	67.7

Volume of Sockeye Salmon Runs Each Year in Bristol Bay

Table B.2: Using Table B.1 to calculate the volume for each year.

Year	Volume (MMCF)
2001	3.41
2002	2.35
2003	3.58
2004	5.55
2005	5.65
2006	5.58
2007	5.93
2008	5.35
2009	5.44
2010	5.1

Continued on next page

Table B.2 – continued from previous page	
Year	**Volume (MMCF)**
2011	4.33
2012	3.96
2013	3.34
2014	5.25
2015	6.98
2016	6.37
2017	7.23
2018	7.34
2019	6.57
2020	6.79
2021	7.26

Average Annual Harvest For Salmon in Bristol Bay

Species	**Harvest**
Sockeye	28,100,000
Chinook	39,571
Chum	1,100,000
Coho	95,583
Pink	510,000
Total	**29,845,154**

Table B.3: Average annual commercial harvest for each salmon species from (2001 − 2020) [Elison et al., 2022]. Pink Salmon are reported in even years because of their two year life cycle pattern.