Spora: A Journal of Biomathematics

Volume 9 Article 3

2023

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Recommended Citation

Macaulay, Rachel; Barrett, Emily; Penunuri, Grace; and Goldwyn, Eli E. (2023) "A Statistical Analysis of the Change in Age Distribution of Spawning Hatchery Salmon," *Spora: A Journal of Biomathematics*: Vol. 9, 12–19.
DOI: 10.30707/SPORA9.1.1675492827.538909
Available at: https://ir.library.illinoisstate.edu/spora/vol9/iss1/3

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Cover Page Footnote

The authors would like to thank the DIPAC research manager Adam Zaleski for many consultations of the AMP report. We would also like to thank two anonymous reviewers for their helpful feedback.

Intercollegiate Biomathematics Alliance

SPORA
A Journal of Biomathematics

ISSN 2473-3067 (Print)
ISSN 2473-5493 (Online)

A Statistical Analysis of the Change in Age Distribution of Spawning Hatchery Salmon

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Abstract

Declines in salmon sizes have been reported primarily as a result of younger maturation rates. This change in age distribution poses serious threats to salmon-dependent peoples and ecological systems. We perform a statistical analysis to examine the change in age structure of spawning Alaskan chum salmon *Oncorhynchus keta* and Chinook salmon *O. tshawytscha* using 30 years of hatchery data. To highlight the impacts of this change, we investigate the average number of fry/smolt that each age of spawning chum/Chinook salmon produce. Our findings demonstrate an increase in younger hatchery salmon populations returning to spawn, and fewer amounts of fry produced by younger salmon compared to older salmon. These results suggest the potential risks associated with younger spawning salmon and aim to help better understand salmon behavior in order to sustain and protect healthy salmon populations.

Keywords: two-proportion Z-test, spawning hatchery salmon, age structure, body size decline, fecundity variation

1 Introduction

The body size of an organism is a particularly significant trait that influences fertility, lifespan, ability to survive, and value by humans. A 2020 study concluded that the body size of Alaskan salmon are declining, and the rate of decline has significantly accelerated since 2000 [16]. Recent studies present strong evidence that climate change, harvest, and human-caused environmental damage may be the cause of widespread body size declines across fish ranging from Amazonia [12] to the Celtic sea [4], as well as in mammals such as Soay sheep in Scotland [17]. While our focus is on the effect of body size on reproductive success, previous studies [2] have shown that even small changes in fish body size can have a large impact on mortality through feedback loops. The decline of salmon sizes is primarily a result of a decline in age-at-maturity; however, the exact cause of salmon returning to spawn at younger ages is largely unknown [16].

Pacific salmon contribute to overall human well-being and are integral to freshwater, riparian, and terrestrial ecosystems [11]. Their annual return to their natal freshwater streams bring nutrients from the ocean to supply various plants and predator species of these ecosystems [6]. Salmon-dependent communities rely on their return to contribute to central ways of life. The deep relationship between indigenous peoples and salmon date back to 12,000 years, playing a key role in physical, social, economic, cultural, spiritual, psychological, and emotional wellness [5].

In 1959, Alaska salmon populations reached an all time low due to fish traps and weak enforcement of fishing regulations [21]. In response, hatchery implementation in Alaska became increasingly popular in the 1970s as an effort to help mitigate the catastrophic population declines and recovering salmon populations [10]. Average annual commercial harvests have improved by 800% since 1974, due to a combination of favorable environmental conditions, limited fishing effort, abundance-based harvest management, habitat improvement and protection, and hatchery production [23].

Alaska salmon populations remain well managed and sustained (largely due to hatchery implementation), unlike other depleting Pacific salmon populations elsewhere. Hatchery implementation generated a widespread variability in the status of the five salmon stocks in different locations across the state. For example, from 1994 to 2005, average annual hatchery contributions in southeast Alaska were 71% for chum salmon, 22% for coho salmon, 21% for Chinook salmon, 13% for sockeye salmon, and 2% for pink salmon [7, 13].

Healthy salmon abundances provide strong support across ecosystems and allow Alaskans to depend on salmon for cultural values, food security, and job opportunity. A decline in salmon sizes has potential to jeopardize these ecosystems and the salmon-dependent peo-

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ples of Alaska [15]. Smaller salmon carry less nutrients than larger salmon, threatening the health of humans and other species of plants and animals [11]. Commercial fisheries financially suffer as a consequence of smaller salmon sizes [16]. Additionally, previous research has shown that reproductive output in fish increases with body size, which suggests that larger (and likely older) salmon produce more offspring than smaller (and likely younger) salmon [3].

We first examine the change in age structure of chum and Chinook salmon over the course of 30 years of data from Douglas Island Pink and Chum, Inc's (DIPAC), Sheep Creek Hatchery (SCH), and Macaulay Salmon Hatchery (MSH) locations in Juneau, Alaska. We then investigate how this change in age structure impacts production of chum fry and Chinook smolt to better understand the significance of a changing age structure. Our analysis is restricted to chum and Chinook salmon species as DIPAC only records age-date for chum and Chinook species. Following the results of [16], which found that 88% of the change in mean salmon size can be attributed to a shift in age structure, we focus entirely on changes in the age distribution and its effect on fecundity for both salmon species. We use fecundity as a measurement of the surviving fry/smolt that are released into the ocean.

We show that the age of spawning chum and Chinook salmon that return to DIPAC hatchery facilities is declining. Accumulating evidence from recent studies suggest that younger maturation rates are likely the result of climate change and competition at sea of wild and hatchery salmon stocks [14, 16]. Consequences of this shifting age structure are detrimental to humans, land, and predators; smaller salmon sizes threaten food security, ecosystem health, and harvest profit.

2 Data

Alaska hatcheries are designed to sustain and enhance salmon resources through incubating fertilized eggs and releasing the resulting juvenile salmon into the ocean [23]. Juvenile salmon imprint on their rearing locations prior to being released into the ocean, and eventually return to the same location as a mature adult [23]. DIPAC is one of the state's 25 private-non-profit salmon hatcheries that was established in 1976. DIPAC currently incubates, rears, and releases four species of Pacific salmon: Chinook *Oncorhynchus tshawytscha*, chum *O. keta*, coho *O. kisutch*, and sockeye salmon *O. nerka*.

Our analysis is based upon DIPAC's 2021 Annual Management Plan (AMP), provided by the Alaska Department of Fish and Game website, that fulfills the requirements of section 5 of the Alaska Administration Code 40.840 [1]. These data includes yearly egg production goals, plans for broodstock development, and harvest management of hatchery returns.

For chum salmon, we use data from the MSH and SCH sections of Tables 7 and 8 of the 2021 DIPAC AMP [1]. For Chinook salmon, we use data from Table 11. We organize the age class data by both return and brood year. Return year is defined as the year adult salmon return to the hatchery to spawn. Brood year is defined as the year eggs are collected and fertilized. We use data organized by return year to examine the change in the age distribution of returning chum and Chinook salmon. We use data organized by brood year to investigate the average number of fry/smolt produced by spawning chum/Chinook salmon. For chum salmon, the brood year data spans from 1984–2017 and return year data spans from 1987–2020. For Chinook salmon, brood year data spans from 1987–2018 and return year data spans from 1994–2020. Excel files with these data organized both by species and by brood year and return year are available on GitHub [18].

SCH (active 1984–1996) and MSH (active since 1987) are DIPAC's two production sites with hatchery facilities that collect returning salmon for breeding purposes. The other production sites (listed in the AMP report) utilize returning salmon for harvest purposes. We use SCH and MSH data to attain broodstock data in order to accurately analyze fry production. Return counts include both male and female salmon.

An important difference between chum and Chinook salmon species is that the chum species return to spawn between three and six years old while the Chinook species return to spawn between two and seven years old. However, in 1998 there are 13 eight-year-old Chinook salmon that returned to spawn. Since there are so few eight-year-old Chinook salmon, we treat these 13 salmon as seven-year-olds that returned in 1998.

The age of the spawning salmon is calculated based on their brood year, the year that a spawning salmons' eggs are collected and fertilized. This is different than the year that the juvenile salmon are released into the ocean. For both chum and Chinook salmon, the fertilized eggs are incubated in the fall. Juvenile chum are released as fry the following spring, while juvenile Chinook salmon spend an additional year at hatchery facilities before being released into the ocean in their second spring.

3 Results

3.1 Comparing changes in the age distribution of spawning salmon

Our first goal is to determine if salmon are returning to spawn at younger ages today than they were thirty years

ago. There are no obvious changes in the time series data, so in order to determine how the age distributions are changing overtime, we total the number of salmon returning for the given time span, divide the time span in half, and then compare the proportions of the total amount that return in each period to determine if there is a statistically significant change in the amount of salmon returning at an earlier age. For chum salmon, we compare proportions of returning salmon from 1987–2003 and 2004–2020. For Chinook salmon, we compare proportions of returning salmon from 1994–2007 and 2008–2020. To perform this analysis, we conduct two proportion Z-tests for both Chinook and chum salmon. We repeated this analysis organizing both species of salmon by brood year and found similar results, see Appendix for details.

For both Chinook and chum age distribution comparisons, we group ages of returning salmon due to data limitations. For chum salmon, there are several years that have extremely low numbers of three- and six-year-old salmon, and for Chinook salmon, there are several years with low numbers of two- and seven-year-old salmon. In analysis, we grouped ages 3–4 and 5–6 for chum salmon, and ages 2–5 and 6–7 for Chinook salmon. Grouping the ages of salmon in this manner leads to reduced standard errors, and for overall analysis, it gives us a more complete picture of the age distribution changes between older and younger salmon.

3.1.1 Chum salmon age distribution

The time series data on the yearly number of chum salmon returning ranges from 1987–2020. Our null hypothesis is: the proportion of three- and four-year-old chum salmon returning to spawn from 1987–2003 is the same proportion in 2004–2020. Our alternative hypothesis is: the proportion of three- and four-year-old chum salmon returning to spawn from 1987–2003 is the less than the proportion in 2004–2020.

The results from this test show an increase in the proportion of three- and four-year-old salmon that return to spawn from 1987–2003 to the years 2004–2020, from 68.56% to 73.53% as shown in Table 1. With that, there is a decrease in the proportion of five- and six-year-old salmon that return to spawn in the second time period, with 31.44% returning from 1987–2003 and 26.47% returning from 2004–2020. The yearly proportions of these two groupings for chum salmon can be found in Figure 1. Since the sample size is large, we assume these proportions are normally distributed and therefore use a two proportion Z-test. The results show a p-value <0.001, which indicates that there is strong evidence to reject the null hypothesis and conclude that the proportion of three- and four-year-old salmon returning to spawn from 1987–2003 is less than in 2004–2020.

Table 1: Number and proportion of returning chum salmon by return year.

Age	1987–2003	%	2004–2020	%
3–4	2,035,347	68.56%	3,031,199	73.53%
5–6	933,508	31.44%	1,090,928	26.47%
Total	2,968,855	100%	4,122,127	100%

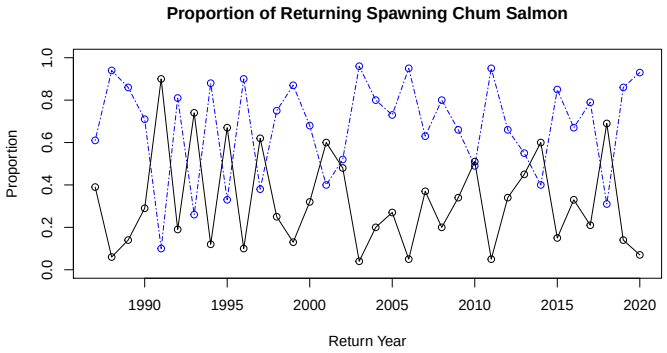

Figure 1: The proportion of returning spawning chum salmon for return years 1987–2020 divided into two age groups (in years): 3–4 (blue), 5–6 (black).

3.1.2 Chinook salmon age distribution

The time series data on the number of chum salmon returning ranges from 1994–2020. As previously mentioned, the age range for returning chum salmon (3–6) is smaller than the returning age range for Chinook salmon (2–7). Our null hypothesis is: the proportion of two- to five-year-old Chinook salmon returning to spawn from 1994–2007 is the same proportion in 2008–2020. Our alternative hypothesis is: the proportion of two- to five-year-old Chinook salmon returning to spawn from 1994–2007 is the less than the proportion in 2008–2020.

The data from this test show an increase in the proportion of two- to five-year-old salmon that return to spawn from 1994–2007 to the years 2008–2020, from 80.50% to 88.84%, also shown in Table 2. With that, there is a decrease in the proportion of six- and seven-year-old salmon that return to spawn in the second time period, with 19.50% returning from 1994–2007 and 11.16% returning from 2008–2020. The yearly proportions of these two groupings for chum salmon can be found in Figure 2. Since the sample size is large, we assume these proportions are normally distributed and therefore use a two proportion Z-test. The results show a p-value <0.001, which indicates that there is strong evidence to reject the null hypothesis and conclude that the proportion of two- to five-year-old salmon returning to spawn from 1994–2007 is the less than the proportion of two- to five-year-old salmon returning from 2008–2020.

3.1.3 Comparison of the proportion of returning n-year-old Chinook salmon

With the Chinook data, we preformed a chi-squared test for association to determine if the proportion of an n-year-old salmon returning to spawn from 1994–2007 is different than the proportion of n-year-old salmon returning in 2008–2020. These data are presented in Table 3. We did not perform this test for chum salmon as there were many years with low numbers of three- and six-year-olds. After performing this test in R, we find p-value <0.001 for each age, and are able to conclude that there is strong evidence that suggests that the proportion of an n-year-old salmon returning to spawn from 1994–2007 is not the same as the proportion in 2008–2020.

Table 2: Number and proportion of returning Chinook salmon by return year.

Age	1994–2007	%	2008–2020	%
2–5	13,906	80.50%	13,670	88.84%
6–7	3,369	19.50%	1,717	11.16%
Total	17,275	100%	15,387	100%

3.2 Comparing changes in offspring production by age

Our second goal is to explore the significance of the changing age distribution of spawning salmon. We would like to investigate the relationship between fecundity and the age of the returning salmon. Unfortunately, we are unable to do this directly, because egg data are not available. Instead we use the number of fry/smolt released from the earlier brood year as a measurement of the egg quantity.

To help uncover the relationship between age of spawning salmon and the number of surviving juveniles released into the ocean, we perform multiple linear regression and compare the coefficients. We group each species of salmon as described in section 3.1 so that the coefficients correspond to different ages of spawning salmon. Due to data availability, for chum salmon, the fry production is averaged from 1987–2017, while Chinook salmon smolt production is averaged from 1994–2018. We base our multiple linear regression model off of the standard formula:

$$Y = b_1X_1 + b_2X_2 + b_3X_3 + \cdots + b_nX_n + \epsilon \qquad (1)$$

The predictor variables X_n in (1) represent the number of returning salmon in age class n. Each b_n predicts the average number of fry/smolt, that survive until release, produced by an n-year-old in a given year. The response variable Y represents the number of fry released from a given brood year.

Our model assumes that the survival rate from fertilized egg to fry/smolt is constant across the time span of the data. The b_n parameters are the tell all in whether certain aged salmon are producing more or less fry/smolt when compared to other aged salmon. Note that $b_0 = 0$ because fry/smolt cannot be created without spawning salmon. It is also important to note that the data do not distinguish between male and female salmon, and therefore neither do the b_n. The b_n calculate the average number of fry/smolt produced for all returning

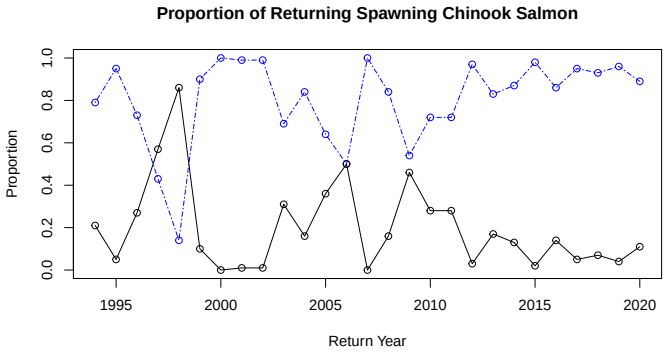

Figure 2: The proportion of returning spawning Chinook salmon for return years 1994–2020 divided into two age groups (in years): 2–5 (blue), 6–7 (black).

Table 3: Number and proportion of returning Chinook salmon divided by individual age groups.

Age	1994–2007	%	2008–2020	%
2	829	5%	8	0%
3	800	5%	1,555	10%
4	3,109	18%	2,992	19%
5	9,168	53%	9,115	59%
6	3,274	19%	1,717	11%
7	95	1%	0	0%
Total	17,275	100%	15,387	100%

Table 4: Regression results for average chum fry production by age groups.

Age	Estimate	Std. Error	95% CI
3–4	83.03	16.35	[66.68, 99.38]
5–6	261.57	45.92	[215.65, 307.49]

Table 5: Regression results for average Chinook smolt production by age groups.

Age	Estimate	Std. Error	95% CI
2–5	90.22	25.82	[64.40, 116.04]
6–7	305.16	121.17	[183.99, 426.33]

salmon, therefore, assuming an equal ratio of male and female salmon, each female salmon produces approximately twice as many fry/smolt.

We perform multiple linear regression for both chum and Chinook salmon. As stated in previous sections analysis, we grouped ages of returning salmon due to data limitations. We use the same groupings listed in section 3.1; once again allowing for reduced standard error and a more general sense of older salmon versus younger salmon. These groupings of ages are reflected in b_n where n represents the combined age groups rather than individual age groups.

3.2.1 Chum

For the chum multiple linear regression, b_1 represents the average number of fry produced by three- and four-year-old spawning salmon and b_2 represent the average number of fry produced by five- and six-year-old spawning salmon. The results from the analysis are shown in Table 4 and yield the following equation:

$$\hat{Y} = (83.03)X_1 + (261.57)X_2 \tag{2}$$

A key result is the two confidence intervals do not intersect, indicating that the difference between these two groups is statistically significant. The average number of fry produced by older spawning salmon is significantly greater than the average fry produced by younger spawning salmon. Furthermore, we find $R^2 = 0.8272$.

3.2.2 Chinook

For the Chinook multiple linear regression, b_1 represents the average number of smolt produced by two- to five-year-old spawning salmon, and b_2 represent the average number of smolt produced by six- and seven-year-old spawning salmon. Table 5 provides the results for this analysis and we find the equation:

$$\hat{Y} = (90.22)X_1 + (305.16)X_2 \tag{3}$$

Once again the two confidence intervals produced do not intersect. These results provide strong evidence that on average, the older spawning Chinook salmon produce more smolt than the younger spawning Chinook salmon. Additionally, we find $R^2 = 0.6576$.

4 Discussion

We provide strong evidence that chum and Chinook salmon are returning to spawn at younger ages in Juneau, Alaska than they were historically. Our study suggests that these younger salmon that are returning to spawn are producing fewer fry than older salmon, which poses a serious threat to the health of salmon populations and beyond.

Previous studies have found that younger maturation explains 88% of the statewide decline in mean salmon size [16]. The direct cause of younger maturation is unknown, but recent studies suggest associations with changes in climate and competition at sea [16]. Moreover, various environmental factors might increase natural mortality in the ocean, prompting salmon to return to spawn at younger ages [16].

Humans, predators, and the land benefit from all stages of the salmon life cycle. Humans reap the cultural, dietary, and economic benefits, which begin to diminish when salmon sizes decline. Smaller salmon sizes weaken the deep cultural connection between salmon and indigenous peoples who have been evolving alongside salmon for thousands of years [5]. Additionally, smaller salmon sizes are potentially catastrophic to the economy from commercial, recreational, and subsistence respects: less flesh on salmon bones correspond to profit reduction [16]. Likewise, smaller salmon sizes reduce the amount of nutrients brought to consumers, especially to rural salmon dependent communities [15].

When salmon return to their natal streams to spawn, their bodies transport an abundance of nutrients from the ocean into these freshwater streams. Salmon supply marine mammals, land mammals, and birds with energy that they need to survive and migrate, thus spawning salmon abundance can be used as an indicator of overall population health and the biodiversity of a freshwater area [9]. Salmon carcasses further the transport the ocean nutrients to the vegetation surrounding spawning salmon grounds [6]. Nutrients provided by the salmon carcasses are believed to enhance the productivity and overall health of the streamside vegetation [6]. Consequently, reduced salmon sizes have the potential to deplete the biological integrity across ecosystems.

Note that the data on the age of return and fry/smolt production are entirely based on hatchery salmon popu-

lations. Hatcheries offer a unique opportunity to get data on relatively large populations and are well curated and tracked to enable statistical analysis. However, there are often important differences between hatchery salmon and wild salmon, and caution should be used in extending results from our study to natural populations.

Climate change, food availability, and spread of disease impact growth rates, metabolism, and survival rates across a variety of animal populations [8, 24, 22]. The impact of these events, specifically on hatchery salmon, are complex and multifaceted; thus, we choose to limit the scope of our work and therefore do not include these external factors. Researching these factors could provide a better understanding of this system and we believe that it would be an interesting direction for future research.

Further studies on the age structure of hatchery salmon would strengthen this analysis and generate a more holistic understanding of salmon behavior. For example, we examined two of the five Pacific salmon species in this paper. Extending this exploration among all five species across other salmon hatchery locations both within and outside of Alaska could help identify behavior patterns between species. Data collection on egg counts from returning salmon for each return year, as opposed to fry/smolt counts for each brood year, could provide a more accurate evaluation of salmon fecundity, as would data on the sex of the returning salmon. Size declines in salmon have been observed in the decades prior to the establishment of hatcheries [20]; thus, we expect an analysis over a longer time period to result in more substantial effects that could help reveal the cause of the shift in age structure. Additional studies from other geographic areas focusing on the effects of climate change or harvest on the age distribution of salmon would also contribute to uncovering the direct cause, and allow for a better understanding of the relationship between humans and the natural world.

Author Contributions

RM found and interpreted the data. EG suggested the statistical methods, edited the manuscript, and supervised the project. RM, EB, and GP equally contributed to the statistical analysis and writing of the manuscript.

Appendix

This appendix provides supplemental analysis of the age of returning salmon organized by brood year.

Table 6: Number and proportion of returning chum salmon by brood year.

Age	1984–1999	%	2000–2014	%
3–4	2,018,304	67.68%	2,752,617	72.60%
5–6	963,848	32.32%	1,038,982	27.40%
Total	2,982,152	100%	3,791,599	100%

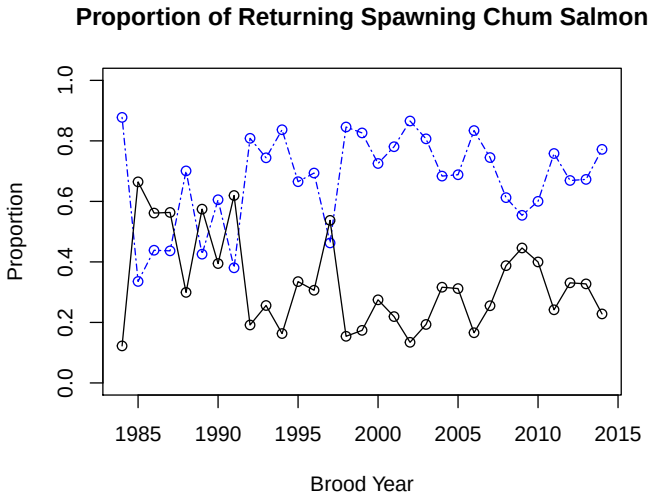

Figure 3: The proportion of returning spawning chum salmon for brood years 1984–2014 divided into two age groups (in years): 3–4 (blue), 5–6 (black).

Chum salmon age distribution by brood year

The time series data on the yearly number of returning chum salmon ranges from 1984–2014. Our null hypothesis is: the proportion of three- and four-year-old salmon returning to spawn from 1984–1999 is the same proportion in 2000–2014. Our alternative hypothesis is: the proportion of three- and four-year-old salmon returning to spawn from 1984–1999 is the less than the proportion in 2000–2014.

The results from this test show an increase in the proportion of three- and four-year-old salmon that return to spawn from 1984–1999 to the years 2000–2014, from 67.68% to 72.60% as shown in Table 6. There is a decrease in the proportion of five- and six-year-old salmon that return to spawn in the second time period, with 32.32% returning from 1984–1999 and 27.40% returning from 2000–2014. Additionally, we use R to compute the significance of the change in proportions and get a p-value <0.001, which indicates that there is strong evidence to reject the null hypothesis and conclude that the proportion of three- and four-year-old salmon returning to spawn from 1984–1999 is less than the proportion in 2000–2014.

Table 7: Number and proportion of returning Chinook salmon by brood year.

Age	1987–2000	%	2001–2013	%
2–5	13,652	80.03%	10,420	86.83%
6–7	3,407	19.97%	1,581	13.17%
Total	17,059	100%	12,001	100%

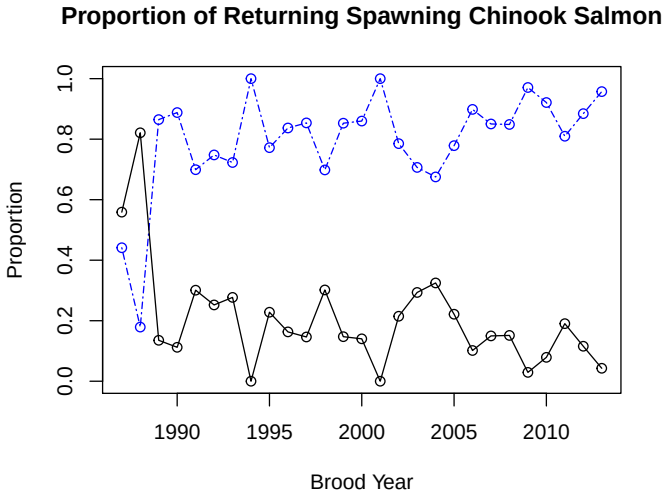

Figure 4: The proportion of returning spawning Chinook salmon for brood years 1987–2013 divided into two age groups (in years): 2–5 (blue), 6–7 (black).

Chinook salmon age distribution by brood year

The time span for the data on the number of chum salmon returning ranges from 1987–2013. Our null hypothesis is: The proportion of two- to five-year-old salmon returning to spawn from 1987–2000 is the same proportion in 2001–2013. Our alternative hypothesis is: the proportion of two- to five-year-old salmon returning to spawn from 1987–2000 is the less than the proportion in 2001–2013.

The data from this test show an increase in the proportion of two- to five-year-old salmon that return to spawn from 1987–2000 to the years 2001–2013, from 80.03% to 86.83%, also shown in Table 7. With that, there is a decrease in the proportion of six- and seven-year-old salmon that return to spawn in the second time period, with 19.97% returning from 1987–2000 and 13.17% returning from 2001–2013. We then use R to compute a p-value <0.001, which indicates that there is strong evidence to reject the null hypothesis and conclude that the proportion of two- to five-year-old salmon returning to spawn from 1987–2000 is the less than the proportion of two- to five-year-old salmon returning from 2001–2013.

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