Examining environmental factors that contribute to juvenile Chinook salmon growth in the Salmon River Basin, Idaho

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**Abstract**

Over the past century, salmon runs in the Columbia River have been reduced to 6-7% of their historical size. The Salmon River in Idaho is a tributary of the Columbia River, and provides spawning habitat for a range of ESA (Endangered Species Act) threatened salmonids including Chinook salmon (*Oncorhynchus tshawytscha*). Different salmon bearing streams in the Salmon River Basin have significantly different juvenile Chinook downstream survival rates through the Snake and Columbia River hydropower system. To understand how conditions in natal streams affect juvenile Chinook, somatic growth from otoliths was measured in seven streams in the Salmon River Basin from 2003-2016 in conjunction with in-stream environmental monitoring data and publicly available local climate data. Our results indicate that El Niño/La Niña weather patterns, stream temperature, flow, and stream productivity patterns all have significant effects on the somatic growth rate of Chinook in the Salmon River Basin. Stream temperature was positively correlated with Chinook somatic growth within the observed temperature range. Somatic growth was highest during years with mild or nonexistent El Niño/La Niña conditions, and the lowest during years with extreme El Niño or La Niña conditions. Indicating that extreme temperature and flow events depressed in-stream growth. The results suggest that increased weather variability under predicted climate change scenarios may adversely affect Chinook growth in the upper Columbia River tributaries.

**Introduction**

Salmon populations on the west coast of the United States have declined precipitously over the past century([Gresh et al. 2000](https://docs.google.com/document/d/1ZkM-rT4erfvl-i7Sb1Fm-AW_uxgLn8D0WHNP3EbiUxY/edit#heading=h.35nkun2)). The Columbia River historically supported salmon runs between 10-16 million fish([Gresh et al. 2000](https://docs.google.com/document/d/1ZkM-rT4erfvl-i7Sb1Fm-AW_uxgLn8D0WHNP3EbiUxY/edit#heading=h.35nkun2)), but as of the year 2000 has been reduced to 6-7% of historical size ([Gresh et al. 2000](https://docs.google.com/document/d/1ZkM-rT4erfvl-i7Sb1Fm-AW_uxgLn8D0WHNP3EbiUxY/edit#heading=h.35nkun2)). The Salmon River supports wild ESA (Endangered Species Act) threatened stocks of spring and summer run Chinook salmon(*Oncorhynchus tshawytscha*), threatened steelhead (*Oncorhynchus mykiss*) , and endangered sockeye salmon(*Oncorhynchus nerka*) (NMFS Federal Register Vol. 79, No. 71. April 14, 2014).

The Salmon River is the longest completely undammed river in the continental US (Palmer 1996). Chinook and steelhead fry rear together in streams before beginning out-migrations down the Salmon River, Snake River hydropower system, and eventually through the Columbia River hydropower system. While the Salmon River itself is relatively un-modified, out-migrating salmon must pass through a highly modified downriver hydropower system to reach the ocean. Smolts must navigate the four Lower Snake River Dams, the four Lower Columbia River Dams, and the resulting reservoirs and tail races in order to reach the Pacific Ocean. In this highly modified environment, survival from rearing streams in the Salmon River to Lower Granite Dam (the first of the four lower Snake River Dams) ranged from 7.8% to 38.5% between 1992 and 1999 (Zabel and Achord 2004). Out-migrating smolts must pass through an additional 7 dams after Lower Granite before reaching the Columbia River Estuary. Chinook survival from 1999-2017 between Lower Granite Dam and the tale race of Bonneville Dam (The lowest dam on the Columbia River) averages 44.5% (Widener et al. 2017). Smolt-to-Adult return rates among Snake River Chinook have declined from 4.3% between 1964-1969 to 1.1% since 2000 (NPCC 2018). This return rate is well below the NPCC’s (Northwest Power and Conservation Council) 2%-6% target (NPCC 2018). With so few fish surviving to eventually return and spawn, understanding the reasons behind small differences in survival becomes extremely important.

During outmigration from the Salmon River, juvenile Chinook from different tributaries pass through Lower Granite Dam generally between April - July (Achord et al. 1996). Within this out-migration window, migrating timing is determined both by population (Achord et al. 1996), as well as fish size (Zabel 2002). Long-term survival studies across Salmon River rearing streams have shown that downstream survival through the hydropower system varies significantly between different rearing streams (Zabel and Achord 2004). Differing environmental factors in rearing streams such as productivity and temperature may be responsible for the differences in observed migrating timing and downstream survival rates across both streams and years.

Streams and rivers in the Columbia River Basin are often inherently oligotrophic. Streams in the Salmon River are usually nutrient limited by either nitrogen, phosphorus, or both (Sanderson et al. 2009a, Thompson et al. 2003). There are also large differences in productivity between streams that are geographically very close to each other (Sanderson et al. 2009). These differences likely are a result of different levels of mineral leaching from the underlying substrate as well as different inputs of allochthonous biological material. This naturally occurring nutrient limitation has been exacerbated by long-term declines in salmon returns from historical levels (Scheuerell et al. 2005). Import of marine-derived nutrients from post-spawning salmon carcasses has declined as salmon runs have declined. In some cases there has been an estimated net negative flow of nutrients out of the system, as out-migrating juveniles remove more biomass from the system than is replaced by returning adult carcasses (Scheuerell et al. 2005). This nutrient limitation has the potential to limit food availability for rearing salmonids(Chederholm et al. 1999), and increase intra-specific competition for scarce resources. Density dependent effects on Chinook survival have been observed in the Salmon River (Achord et al. 2003), which may indicate growth is nutrient limited.

Another important environmental factor that plays a role in Chinook growth is temperature. Chinook salmon are poikilothermic, and as such have metabolic rates largely determined by the surrounding temperature of their environment. When ambient temperatures exceed levels for optimal physiological and metabolic function, detrimental physiological effects and death can result (Richter et al. 2005, Sullivan et al. 2000, others). Chinook salmon in laboratory settings begin to produce heat-shock proteins (hsp70) after several-hour exposure to 20° Celsius water (Mesa et al. 2002); and acute mortality begins to occur when ambient water temperatures reach 24° Celsius (McConnel and Blahm 1970; Richter et al. 2005; Sullivan et al. 2000;). Even when temperatures do not reach harmful levels, high ambient water temperatures above growth optima causes lower growth (Bisson and Davis 1976; Brett et al. 1982; Garling and Masterson 1985; McCullough et al. 2001; Richter et al. 2005) due to increased basal metabolic activity and energy usage. This high basal metabolic rate results in lower growth rates, as more energy is being wasted on excess basal metabolic activity instead of growth.

Under predicted future climate change scenarios, average temperatures in the Pacific Northwest are expected to increase 1.8°C to 5.4°C by 2070 to 2099 (compared to 1970-1999) (IPCC 2007; National Climate Assessment 2014), and summer precipitation is expected to decrease by an average of 10% (National Climate Assessment 2014). Changes in snowmelt timing are also predicted to change streamflow patterns (National Climate Assessment 2014), reducing the supply of water that is available for use. These predicted changes in temperature and precipitation will likely have profound effects on the fish that utilize these streams for spawning and rearing.

One way to examine the possible effects of future climate change scenarios is to study the effect that past extreme weather events have had on Chinook growth. El Niño/La Niña weather events have a large impact on yearly temperature and rainfall patterns in the Salmon River Basin, and more broadly across Northwestern North America (US Federal Government, NOAA, Climate.gov). Intensity of an El Niño/La Niña pattern is measured with an intensity index that coalesces complex regional weather patterns into a value in which to make spatial and temporal comparisons (US Federal Government, NOAA, Climate.gov). For example, in 2015 a very strong El Niño Index existed concurrently with unusually high temperatures, and unusually low rainfall across much of the Pacific Northwest, Including the Salmon River Basin (US Federal Government, NOAA, Climate.gov). These weather patterns were similar to predicted higher temperature patterns under future climate change scenarios (IPCC 2007; National Climate Assessment 2014). By studying the effects of these anomalous weather patterns on juvenile Chinook growth, inferences about responses to future climate change scenarios can be made. Additionally, improved understanding of how yearly El Niño/La Niña patterns affect growth can aid managers in estimating survival.

Success during early life stage/rearing can have long lasting effects on the chances of survival during the subsequent life stages. Increased relative size of juvenile Chinook within a population has been shown to increase the chances of downstream survival (Zabel and Achord 2004). Additionally, fish length is directly related to downstream passage date through Lower Granite Dam (Zabel and Achord 2004). Larger Chinook are able to out-migrate earlier, and thus may be able to avoid hazards and predators that fish out-migrating later cannot avoid (Zabel and Achord 2004).

Being able to tie environmental factors such as stream productivity, water temperature, flow, and climate to fish growth is extremely useful. It allows for a better understanding of why current regional trends in salmon production and downstream survival exist, as well as providing insight into possible growth under predicted climate change scenarios. This study began in earnest in 2003, with continuous data collected yearly through 2016. The goals of this study were:

1) To pair as much biotic and abiotic information from the streams as possible with juvenile Chinook growth rates.

2) To model growth with corresponding environmental factors in and around the streams to pair variability in growth with specific environmental metrics.

3) To examine how different water temperature and local climate regimes affect Chinook somatic growth, including extreme climate events.

**Methods**

Fish collection and processing:

For this study, seven streams across the Salmon River Basin in Idaho were chosen for sampling: Marsh Creek, Cape Horn Creek, Elk Creek, Bear Valley Creek, Valley Creek, Lake Creek, and South Fork Salmon River (Figure 1). These streams are part of an on-going and long-term PIT (passive integrated transponder) tagging project in the region. The specific streams were chosen from a larger set of streams in the PIT tagging study in order to represent a range of different average stream temperatures, and a range of different stream productivities. Juvenile Chinook were caught via electroshocking during the summers of 2003-2016 (Figure 2). In years when low numbers of Chinook were caught, incidental PIT tagging mortalities were used to bolster sample sizes. Each year fish were collected from the same stretches of streams where fish for PIT tagging were caught. The majority of fish were caught in early September, in order to be able to examine a larger amount of summer growth. Due to a variety of sampling restrictions in some years, fish were collected from a wider range of times from mid-July through mid-September (Figure 2).

On average, about 10 Chinook and 10 steelhead were caught per stream, per year. A total of 999 Chinook were used for this study. Of those, 978 were juvenile Chinook that had hatched in the spring of their collection year. There were 21 Chinook collected that were precocious males, meaning that they were sexually mature Chinook that hatched in the spring of the previous year, but stayed in the stream for their entire life cycle. They were on average larger (average fork length 112.4mm) compared to average fork length of 66.4mm for sub-yearling juveniles. After collection, fish were euthanized with tricaine methanesulfonate (MS-222), wet weighed to the nearest 0.1g, and fork length and total length measured to the nearest 1mm. Once initial measurements were taken the fish were frozen at -20 degrees Celsius until processing. Once in the lab, otolith processing methods used were almost identical to those used in (Chittaro et al. 2015 and Zabel et al. 2009). Otoliths were extracted using fine-tipped forceps and surgical scissors, and placed in 1.5mL vials for storage. Polishing consisted of mounting otoliths on microscope slides (VWR) with thermoplastic (Crystalbond 509), and polishing using grinding and polishing slurries (Buehler 35 micron alumina oxide, 5.0 micron alumina oxide, and 1.0 micron alumina oxide micropolish). Otoliths were polished until cores were visible and daily increments from the edge inward were visible (Chittaro, Zabel, Beckman, Larsen, & Tillotson, 2015; Volk, Bottom, Jones, & Simenstad, 2010). Digital images were captured using a camera (Leica DFC450) mounted to a compound scope (Zeiss). Image Pro Plus Version 7.0 (Mediacybernetics) was used to analyses daily growth increments from the images. We measured distance from otolith core to edge (i.e., otolith radius at time of capture, Oc) and to as many increments as possible. This resulted in a dataframe whereby each fish had 2 columns:

1) a column of otolith radii and

2) a column of increment widths.

We calculated a 3rd column of fork length at a time prior to capture. Specifically, for each otolith radius (Oa) we estimated fork length (FLa) using the quadratic equation with biological intercept reported in Zabel et al. (2010)

FLa = ((0.096\*(Oa-Ointercept))+(0.000053\*((Oa-Ointercept)\*(Oa-Ointercept)))) + FLintercept

FLa = ((0.096 \* (Oa - 95.8)) + (0.000053 \* ((Oa - 95.8) \* (Oa - 95.8)))) + 21.6

Where mean fish length at hatching (FLintercept) was 21.6mm for spring/summer Chinook and mean otolith radius intercept (Ointercept) at hatching was 95.8 microns for spring/summer Chinook. To constrain the models to pass through these intercepts, we first subtracted the intercept from each individual’s fork length and otolith radius. Using this column of estimated fork lengths we then will calculate average daily growth rate (mm/day) for an individuals’ last 7, 14, 21, and 28 days of life (a), Average daily growth=(FLc-FLa)/a7 to 28days of growth was a reasonable amount of time to estimate growth while in rearing habitats. It should be noted that the growth rate estimate used throughout this study is the average daily growth from the last 7 days prior to capture/death. Corrected values accounting for different dates of capture and size of fish were created and used during modeling to account for these confounding effects.

Temperature and precipitation data collection:

Temperatures were collected with HOBO temperature loggers in each of the streams. Temperatures were recorded every 10 minutes, from May to October from 2003-2016. Temperature data was not available for some streams earlier in the study. HOBOs collected temperature data in Bear Valley and Elk from 2008-2016, Cape Horn from 2009-2016, Lake from 2009-2016, Marsh, South Fork Salmon, and Valley from 2003-2016. Once data was retrieved, daily max, min, and mean temperatures were calculated (Figure 3). In order to fill in missing periods of time, the MARSS package in R was used to compute missing data. MORE ON THIS

Water depth was measured at gauging stations in each stream (Figure 6). Generally depth data was collected during the same periods of time that temperature was collected. The MARSS package was used to compute missing depth data using the same procedure that temperature data was computed. We compiled data on the El Niño and La Niña cycle to examine the effect of larger scale, longer term climatic patterns on growth rate (US Federal Government, NOAA, Climate Prediction Center).

Chinook catch per unit effort was calculated each year during PIT tagging. Electroshocking crews recorded the length of stream that was sampled, along with the total numbers of Chinook that were observed and caught. The catch per unit effort serves as a surrogate for fish density, since site specific density estimates were not available.

Stream productivity and food availability:

Five sites were selected from each stream and marked on a GPS. Sites were selected to be morphologically similar to one another, in order or make comparisons more accurate. Each site was several hundred meters apart from the previous one. Every year, samples were collected from each site in the same location. Water chemistry was collected at every stream at least once a year, and usually twice. Five water samples were taken each time a stream was sampled, one from each site. Acid washed and sterile 125mL bottles were used for collection, and single use 60mL syringes were used for water collection. Samples were frozen, and analyzed within a few months of collection by the University of Washington, School of Oceanography’s Chemical Oceanography Lab. Total nitrogen and total phosphorus, phosphate, and nitrate were measured from each water sample.I n all, there were 1028 water chemistry samples taken. Values were averaged among the five sites for a given stream sampling event.

In order to examine stream productivity, ash-free dry mass (AFDM) and chlorophyll fluorescence per meter3 was measured to determine productivity per unit area of steam bed. During yearly sample collection, one rock was randomly selected from each site at each stream. Rocks were put on ice and driven back to the lab for processing. Each rock was thoroughly scrubbed and rinsed in order to remove all biomass. Rocks were measured for length, width, and height in order to calculate a rough volume for each rock. The rinsed water was subsampled and filtered onto glass fiber filters for AFDM and chlorophyll fluorescence analysis. AFDM samples were dried overnight in a 105 **°**F oven, weighed, and then ashed at 1000**°**F in a muff oven, and weighed again to calculate the mass of organic solids. AFDM per meter3 was back calculated from the subsampling volumes before being divided by the volume of each rock. Chlorophyll samples on filters were extracted in 10mL of HPLC grade acetone in a freezer overnight, before being diluted in pure HPLC grade acetone for fluorometry. Fluorescence was calculated in a dark room using a TD 700 Fluorometer that was regularly calibrated. Blanks were run before and after analysis for quality assurance. In all, there were 1391 AFDM and chlorophyll fluorescence samples taken. Values were averaged among the five sites for a given stream sampling event.

Prey availability was assessed using benthic and drift samples taken at each stream. Benthic samples were taken using a Hess Sampler and placed in 250mL bottles filled with 95% ethanol. Drift samples were taken using drift nets set out for approximately 20 minutes. The total time the nets were in the water, water depth in the net, and flow through the net were calculated in order to calculate and standardize water volume that was sampled for each drift sample. Samples were placed in 250mL bottles with 95% ethanol. Drift and benthic samples were analyzed by Rhithron Associates Inc. Generally, three benthic samples and two drift samples were collected at each stream during a sampling event. Several metrics were calculated from each sample. Total invertebrate biomass, the invertebrate density, and the Shannon-Wiener Index were calculated for various samples. Drift samples and benthic samples from a given stream sampling event were each averaged. Due to financial restraints, not every metric was calculated for every sample. Of the 722 benthic samples and 411 drift samples collected between 2003-2016, invert biomass was calculated for 219 drift samples and 220 benthic samples. 222 drift samples were analyzed for invertebrate density, and 185 benthic samples were analyzed for insect density and Shannon-Wiener Index.

**Pairing growth data with environmental data:**

Using calendar dates, Chinook growth and fork length data was paired with the rest of the environmental data that had been collected. Environmental data was not available for every fish caught. When environmental data WAS collected at the same time as fish, all available data was paired to those fish. When environmental data was not collected at the same time as fish, those fish were not paired with any extra data. Unique identifiers were given to every fish at the time of collection, allowing all available environmental data to be synced from multiple sources to each fish when it was available. Chinook growth rates were compared using generalized linear models (GLM). A total of 17 different environmental metrics were input into GLM models along with fish growth, stream, year, and day of year collected. AIC scores were used to evaluate model success at predicting variability in growth. Models with AIC values less than 2.0 apart from each other were considered indistinguishable.

A primary concern during the analysis was confounding effects from differences in collection date and fish size. Since fish were collected on different dates, and were different sizes. In order to account for this during the analysis, fish growth was standardized by fish size, and to the same window of time as calculated by day of year. Calculated growth rate was divided by the measured fork length at the time of capture. Separately, growth rate from the same 7 day window was used to create a growth estimate from the same window of days. Day of year 234-240 was used to calculate an average 7 day growth for that period of time (as opposed to last 7 days of growth which is what was primarily used for this study). Day of year 234-240 was chosen because the majority of the fish in the study have growth data that falls into this range. Of the 936 Chinook that were in the dataset, 624 (2/3) were collected after day of year 240, and thus daily increment data was available for the 234-240 range. Fish that were collected prior to day of year 240 were excluded from that analysis. Each of these separate corrections was added to the dataset and modeled separately in the same way as the original last 7 days of growth.

**Results**

Stream temperatures fluctuated yearly in an expected pattern. Peak temperatures were usually recorded in the last two weeks of July and the first two weeks of August. Across years CHO consistently had the lowest average temperatures, while VAL, ELK, and BVA consistently had the highest temperatures.

Growth rate varied between both stream and year (Figure 4). ELK, LAK, and SFS had the highest growth, with VAL, MAR, and BVA having intermediate growth, and CHO experiences the lowest overall average growth.

**Comparing growth data to environmental metrics**

For Chinook: A model that contained: the sampling year, the stream that was sampled, the day of year when the fish was sampled, the previous 3 months of el nino and la nina intensity values prior to fish capture, and total nitrogen concentration in the stream water at the time of capture, had the highest success at predicting average daily growth rates over a one week period prior to fish capture with an AIC value of -1,934.7.. Other variables that were present in the top ten models were total phosphorus and current el nino and la nina intensity values at the time of fish capture. Of the top ten models with the lowest AIC values, 4 of them included total phosphorus as a variable, and 5 included total nitrogen. Current el nino and la nina intensity values at the time of fish capture also was included in 5 of the of the top 10 models. The AIC values of the top ten models ranged from -1,934.7 to -1929.1 (Table 1.).

When primary productivity metrics were added in, AIC values increased to -1,442.8 when biomass per cubic meter of stream bed was added, and -1,449.7 when chlorophyll concentration per cubic meter of stream bed was added. When models with invertebrate metrics included were run, AIC values increased further. The models with the lowest AIC values for each invertebrate metric had on average, an AIC value of -609.4, still significantly higher than models that excluded invertebrate metrics.

After this initial modeling with the original growth estimate of last 7 days of growth. Growth corrected by fork length, and growth during day of year 234-240 were both modeled in the same way. The top models from both of these corrected growth estimates had the same environmental variables as the original. The AIC value of the top model with growth corrected by fork length was -8,588 and the AIC value of the top model with day of year corrected was -1,483.

After initially modeling all the streams together, individual streams and individual years were separated and modeled individually. Water temperature measurements were added into the models for each stream. The daily average and daily max, averaged over the same one week period as growth were added into the models.

Streams modeled individually did not have stream temperature included in their top models. When individual years were modeled, stream temperature was included in the top models from 2009-2016. In some cases, stream temperature alone was the most successful at predicting growth rates. From 2003-2008, stream temperature was not in any of the top models that predicted stream growth. Interestingly, the primary temperature dataset used for this analysis was very patchy between 2003-2008. As a result, the primary temperature dataset being used was supplemented by another temperature dataset that was gathered in the same areas by different researchers. It’s possible that discrepancies between these two datasets caused the models between 2003-2008 to exclude temperature from the top models.

Growth rate on average declined over the course of summer months, with the highest growth in early to mid-July, before gradually tapering off through August and September (Figure 5). Average daily water temperature in a one week period was highly correlated with average daily growth rate in Chinook for the same one week period in the same stream(Figure 5). For Chinook, higher water temperature was highly correlated with higher growth in six of seven streams. The seventh stream (Lake Creek) showed no relationship between growth rate and stream temperature within the range of water temperatures that was observed. This is likely because the range of observed temperatures was extremely narrow in Lake Creek compared to the other seven streams. On average, temperatures in Lake Creek that were measured concurrently with fish growth varied less than 2 degrees Celsius while the other six streams in the study varied anywhere from 6-10 degrees Celsius.

Average growth rate was normally distributed across average water depth measurements in the streams, with depths of about 0.5 meters (1.6 feet) correlated to the highest average growth rates (Figure 6). El niño/la niña intensity index concurrent with the measured growth rates, and in intensity index 3 months prior to when fish were growing also showed normal distributions when plotted with average growth rate(Figure 6). On average, the highest growth occurred during years with mild el niño conditions, or no recorded el niño or la niña(Figure 6).

Invertebrate (prey) biomass in the water column was positively correlated with average growth rate (Figure 6), but was not important enough to make it into the top models. However the relationship does exist and is significant. Water chemistry in the form of total nitrogen and phosphorus, or nitrate and phosphate (NO3 and PO4) either showed no relationship to growth, or a slightly negative relationship(Figure 7).

When fitting models to the data, Generalized Additive Models (GAM) were used to fit data that was non-linear. GAMs were used to fit lines to environmental variables that didn’t fit well with linear models when the data was plotted against fish growth. Day of year that the fish were caught, weekly water temperature average when fish were caught, el nino/la nina intensity index, and average weekly water depth when fish were caught all had clear non-linear relationships with average fish growth.

**Relationships between environmental data**

Many significant relationship existed between various environmental metrics we measured in the stream. A correlation matrix was made in order to better visualize the correlations between the various environmental variables that were measured (Figure 8). These relationships gave us confidence that we were accurately quantifying at least some of the processing occurring in these streams. Levels of nitrogen and phosphorus in the water were positively correlated with each other, as well as with primary producer productivity. Primary producer productivity was assessed by measuring both the biomass and chlorophyll concentration of biofilm and epiphytes per meter squared on the stream bed. These relationships make intuitive sense, and helped increase our confidence in our collection methods. The prey biomass and density of stream invertebrates also was positively correlated with primary producer productivity.

When environmental variables showed non-linear relationships to each other, GAMs were used to fit lines to the data. The clearest non-linear trend between the environmental data was the sinusoidal relationship between day of year and water temperature, with peak recorded temperatures usually falling between the last two weeks of July and the first two weeks of August. Other relationships between environmental variables were assumed to be linear.

**Discussion**

Climate change is predicted to increase average temperatures across the Pacific Northwest and elsewhere, and cause more variable rainfall; leading to more variable, warmer stream flows. The extremely hot and dry weather in 2015 is similar to predicted weather trends in the Salmon River. This is a worrying prospect, as growth in 2015 was much lower than on average. While slightly warmer water may have helped fish in some streams grow faster, low water levels may have negated any growth benefits from this. In consistently colder streams such as Cape Horn, higher average water temperatures may actually increase somatic growth of salmonids. While in streams that have been historically warmer, higher water temperatures may surpass ideal levels, leading to a decrease in growth, as more energy is spent on base metabolic rate instead of somatic growth.

The nutrient levels in the water support the growth of the various primary producers in the stream food web. These primary producers in turn, support much of the invertebrate community that Chinook and steelhead rely on. Interestingly, stream chemistry had either no relationship, or a slightly negative relationship to fish growth, but was present in most of the top growth models. The reason for this may be that the chemical compositions of each stream were different enough to be able to relate these differences to the differences in somatic growth. While the biomass and density of the prey base in the streams was not an important variable in models describing fish growth, it did show a significant positive relationship. While food availability does seem to affect growth, it is outweighed by stream temperature and weather patterns in the models.

Stream flow itself was not in the top variables explaining growth, however it is highly related to the el niño/la niña intensity index, which was in many of the top models. The normal distribution between flow and growth is similar to the relationship between growth and the el niño/la niña intensity index. Both extremely low flows, and extremely high flows resulted in a decrease in the average growth rate, with an optimal zone existing at an intermediate flow regime.

Significant differences between average temperature and temperature response on growth rate between streams existed. Within the temperature ranges we measured, growth rate increased with temperature in all streams except LAK, which showed no relationship due to the very narrow range of temperature that was recorded. Water temperature that was recorded concurrently with growth ranged from 5 degrees Celsius to 17.5 degrees Celsius. Average water temperatures peaked in late July, several weeks after average growth rates peaked. Temperatures then steadily declined over the rest of the summer into early fall.

The thermal optima for Chinook in this study was not clearly visible. When plotted against average daily average temperature, Chinook growth does not show any indication of tapering off at the maximum recorded daily average temperatures of 17.5 degrees Celsius. The highest average daily maximum temperature recorded was 22.3 degrees Celsius. In previous studies, Chinook salmon in laboratory settings begin to produce heat-shock proteins (hsp70) after several-hour exposure to 20° Celsius water (Mesa et al. 2002); and acute mortality begins to occur when ambient water temperatures reach 24° Celsius (McConnel and Blahm 1970; Richter et al. 2005; Sullivan et al. 2000;). . The temperature response of the wild Salmon River Chinook cannot be assumed to be the same as the hatchery Chinook broodstock used in previous thermal tolerance studies. However, it can be reasonably assumed that the thermal tolerance of these wild Chinook is within the same general range.

The average daily temperatures and average daily maximum temperatures recorded in these streams came from temperature loggers anchored to substrate. Since there were not temperature loggers placed inside the fish, it is impossible to say what specific temperature a fish chose to reside in. When exposed to these possibly damaging temperatures, Chinook can either stay, or seek thermal refuges. The importance of thermal refuges provided by pools, cutbanks, and large woody debris can’t be overstated. While behavioral responses may help mitigate dangerous daytime temperature extremes, there may be an energetic cost associated with seeking shelter versus active feeding in the water column.

When individual years were modeled, stream temperature was included in the top models from 2009-2016. In some cases, stream temperature alone was the most successful at predicting growth rates. From 2003-2008, stream temperature was not in any of the top models that predicted stream growth. Interestingly, the primary temperature dataset used for this analysis was very patchy between 2003-2008. As a result, the primary temperature dataset being used was supplemented by another temperature dataset that was gathered in the same areas by different researchers. It’s possible that discrepancies between these two datasets caused the models between 2003-2008 to exclude temperature from the top models.

Fish growth was on average lowest during extreme el niño and la niña years, with highest growth during mild el niño years. During la niña years, the Salmon River Basin is cooler on average and has more rainfall. During el niño years, the Salmon River Basin experiences hotter and drier than on average. From the growth data of Chinook, it appears that either of these two climatic conditions in the extreme depress growth. During years of mild la niña, mild el niño, or neither, fish growth rate was much more variable during either extreme. Many fish still grew at the same rate as fish that experienced more extreme la niña or el niño years. However, a large percentage grew significantly faster, indicating that although a mild climate year does not guarantee higher growth, it does appear to provide more of an opportunity for it. The impact on fish from el niño and la niña conditions likely comes in the form of changes in water temperature and flow; with moderate flows and moderate temperatures providing an optimum environment for growth. The interactions of these two variables results in the normal distribution seen between the el niño/la niña intensity index and growth.

The climate in the Salmon River Basin, and more broadly the Pacific Northwest is predicted to become not only hotter and drier, but much more variable. The impact this will have on fish will likely result in growth rates lower than they have been in the past. The rearing streams in the Salmon River Basin are relatively intact compared to the main stem Snake and Columbia Rivers, which have had extensive hydropower development. The rearing phase of the Chinook life cycle helps determine the future survival success of the subsequent life stages downriver. Streams that naturally produce larger Chinook may give them a competitive advantage downstream when navigating predator dense reservoirs. Which current streams consistently produce larger fish may shift in the future as temperature and flow patterns change. This study adds to the body of knowledge on the effect of rearing conditions on Chinook, and specifically that of Salmon River Chinook. From a management and modeling perspective, being able to predict some amount of growth and body condition based on climatic data is extremely useful. Future studies should incorporate downriver survival data with growth and environmental metrics from natal streams.

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