

LANDSCAPE CHARACTERISTICS INFLUENCE CLIMATE CHANGE  
EFFECTS ON JUVENILE CHINOOK AND COHO SALMON REARING  
HABITAT IN THE KENAI RIVER WATERSHED

By

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A Thesis Submitted in Partial Fulfillment of the Requirements  
for the Degree of

Master of Science  
in  
Fisheries

University of Alaska Fairbanks  
August 2020

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## **Abstract**

Changes in temperature and precipitation as a result of ongoing climate warming in south-central Alaska are affecting juvenile salmon rearing habitat differently across watersheds. Work presented here simulates summer growth rates of juvenile Chinook and coho salmon in streams under future climate and feeding scenarios in the Kenai River (Alaska) watershed across a spectrum of landscape settings from lowland to glacially-influenced. I used field-derived data on water temperature, diet, and body size as inputs to bioenergetics models to simulate growth for the 2030-2039 and 2060-2069 time periods, comparing back to 2010-2019. My results suggest decreasing growth rates under most future scenarios; predicted changes were of lower magnitude in the cooler glacial watershed and main stem and more in montane and lowland watersheds. The results demonstrate how stream and landscape types differentially filter a climate signal to juvenile rearing salmon habitat and contribute to a broader portfolio of habitats in early life stages. Additionally, I examined two years of summer water temperature data from sites throughout our study tributaries to assess the degree to which lower-reach sites are representative of upstream thermal regimes. I found that the lower reaches in the lowland and glacial study watersheds were reasonably representative of daily and seasonal main stem thermal conditions upstream, while in the montane study watershed (elevation and gradient mid-way between the lowland watershed) upstream conditions were less consistent and thus less suitable for thermal characterization by a lower-reach site alone. Together, this work highlights examples of the importance of accounting for habitat diversity when assessing climate change impacts to salmon-bearing streams.

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## Acknowledgements

Alaska offers an incredible setting to work as an ecologist and is home to some of the world's best minds in the field. I am lucky to be part of a supportive community of researchers, managers, and stakeholders that work to understand how we can adapt to the changes our world is experiencing.

I am first and foremost grateful to all people of the Kenai Peninsula area who engaged with and supported this work. Ideas from fishermen, explorers, and visitors of all kinds I met while out in the field are found throughout this thesis. Conversations and in-kind support from Sue Mauger with Cook Inletkeeper and Branden Borneman with the Kenai Watershed Forum were invaluable, as was feedback from Brenda Trefon with the Kenaitze Indian Tribe. Kenai Peninsula College provided laboratory space and housing support in Soldotna, and the late Dr. Alan Boraas shared extensive expertise in regional and historical context that will be sorely missed.

My advisors and graduate committee members at UAF comprised a true dream team of experts on the subject matter of this thesis and I am indebted to their support. I have my co-advisors Mark Wipfli and Dan Rinella to thank as the driving forces behind the conception of this research, and for demonstrating by example how to find valuable and meaningful work as a scientist. I am grateful for your mentorship, guidance, and support. Erik Schoen was the most knowledgeable and friendly collaborator and office mate one could hope for in all steps along the way of graduate school. Thank you for your assistance in understanding bioenergetics, programming, and keeping sane in long Fairbanks winters. Jeff Falke was an invaluable source of help in how to address complex problems in statistics and analysis and a source of expertise in water temperature data analysis without which this project would not have been possible. All graduate committee members (from here on referred to as "we") are also co-authors on the two manuscripts presented in this thesis.

I am grateful for the administrative support of the Alaska Cooperative Fish and Wildlife Research Unit, Institute of Arctic Biology, and College of Fisheries and Ocean Sciences especially Kathy Pearse, Monica Armbruster, K.C. Love, and Christina Sutton for their willingness to address the logistical challenges that come with working in remote locales. The Alaska Established Program to Stimulate Competitive Research

(EPSCoR) was the primary financial supporter of this research. The interdisciplinary nature of working with EPSCoR demonstrated the value of approaching science as a two-way conversation: using a community's values to inspire research, and following up with public outreach to ensure one's work has meaning and utility. Thank you in particular to Pips Veazey, Anupma Prakash, and Courtney Breest. I am also grateful for additional financial support from University of Alaska Fairbanks including the Institute of Arctic Biology Summer Graduate Research Award, the Nicholas Hughes Memorial Scholarship, and the University of Alaska Department of Biology and Wildlife.

This research would not have been possible without the expertise and dedication from field and laboratory assistants Christina Mielke and Emily Neideigh. I remain in awe of your knowledge of freshwater invertebrates and ability to put up with me through rain, wind, and mosquitos for a whole summer. Mike Lunde lent his considerable expertise to ageing juvenile salmon scales.

My roots in Alaska have been the primary inspiration for seeing this work through, and for that I have many to thank but most especially my family; parents Ann and Phil, brother Chad, along with aunt and uncle Mike Horne and Mary Pomeroy who have shown me all that Alaska has to offer. Thanks for letting me investigate swamps and mud puddles for hours on end in my younger years to see what lives there and all that has followed since. In Soldotna, Dave and Kathy Wartinbee and John and Molly Messick provided hospitality and friendship that make a place worth knowing.

Finally, throughout this experience my partner Trina McCandless has been the person in my life I've been most excited to share my day with. I am forever grateful for your support through this experience. Thank you, and I love you.

## **General Introduction**

Ongoing climate change has the potential to challenge the long-term viability of wild salmon (*Oncorhynchus spp.*) populations throughout the Pacific Rim (Bryant 2009; Crozier et al. 2008). Particularly in higher latitudes, significant increases in air temperature and precipitation are predicted by the end of the twenty-first century (Markon et al. 2018), driving a complex shift in factors that influence productivity of anadromous habitats such as water temperature (Muñoz et al. 2015a) and flow regime (Ward et al. 2015). In contrast to other regions throughout the Pacific Rim most Alaska salmon populations currently face minimal challenge from anthropogenic habitat degradation and unsustainable harvest. Impacts from climate change thus remain among the least understood determinants of their future persistence. There is debate as to whether the physiological, behavioral, and evolutionary plasticity of Pacific salmon will allow populations to adapt to the habitat transformations posed by climate change (Mantua et al. 2015; Muñoz et al. 2015b).

Life histories and habitats of salmon vary widely and the different influences of climate change are best interpreted as specific to the life stage, species, and stock in question. Anadromous (salmon-bearing) habitat occupies a broad range of environments throughout the Gulf of Alaska region and encompasses lowland, wetland-dominated drainages as well as mountainous, glacial-melt whitewater streams. Water temperature and flow regimes in these varied landscapes respond heterogeneously to broader climate signals (Mauger et al. 2017; Schindler et al. 2008), with some regions serving as climate “refugia” (Isaak et al. 2015) while others will experience more rapid change. Existing research on climate change-driven effects on salmon habitat in Alaska both documents ongoing shifts and suggests future trends. For example, shifts in water temperature and flow regimes since the mid-twentieth century are associated with earlier timing and shortened duration of adult salmon migration in southeast Alaska (Kovach et al. 2013; 2015), with some variability in change likely attributable to differential impact climate impacts on freshwater habitats. Increasing air temperatures drive earlier ice-out dates and are associated with higher growth rates of lake-rearing juvenile sockeye in southwest Alaska (Schindler et al. 2005) as well as higher survival of juvenile Yukon River Chinook salmon (Cunningham et al. 2018). Other investigations

have highlighted likely effects of shifting hydrologic regimes on juvenile drift-feeding behavior (Neuswanger et al. 2015), egg-to-fry survival rates (Shanley and Albert 2014), smolt production (Leppi et al. 2014), and extent of viable spawning habitat (Sloat et al. 2017).

In the salmonid juvenile rearing life stage, water temperature regime and food resources play central and interrelated roles as controls on somatic (body size) growth rate (Mejia et al. 2016). Growth may be limited by low food consumption rates or water temperatures outside the range ideal for metabolism (Beauchamp 2009). The degree to which either water temperature or food resources constrain growth rates appears to vary by individual river system (Beer and Anderson 2011; Chapman 1966). Growth rate offers an important perspective on freshwater habitat conditions for juvenile salmon and steelhead, and may have long-term implications for the productivity (Henderson and Cass 1991), maturation timing (Sloat and Reeves 2014), and other aspects of population dynamics including size-selective mortality and individual fitness (Connor et al. 2002; Ruggerone et al. 2009; Thompson and Beauchamp 2014). Growth rates of Chinook (*O. tshawytscha*) and Coho (*O. kisutch*) salmon in particular may be sensitive to shifts in thermal regime as they reside in lotic freshwater rearing habitat for up to two (for Chinook salmon) or three (for coho salmon) winters before out-migrating to the marine environment (Quinn 2005). Both species of salmon occupy similar habitat niches and co-mingle throughout much of their ranges (Quinn 2005).

In Chapter 1 of this thesis we explored potential impacts of shifting climate regimes on juvenile Chinook and coho salmon growth. We examined how landscape mediates water temperature regime, which in turn mediates growth rates of juvenile Chinook and coho salmon heterogeneously throughout a large, diverse watershed. We collected and employed data on water temperatures, consumption patterns, and their somatic growth rates in three geomorphically distinct tributaries and the main stem of the Kenai River, which supports a high-profile sport, commercial, and subsistence fishery in south-central Alaska. Our broad objective was to identify how varied landscapes within the Kenai watershed mediate consumption and water temperature patterns in juvenile Chinook and coho salmon habitat, which in turn influence individual fish growth rates. Our specific objectives were to use growth simulations to identify the

patterns of a.) thermal regime and b.) diet that influence response of juvenile growth rate to future climate and diet scenarios. The three sub-basins differed substantially in landscape characteristics including elevation and gradient. As stream water temperatures respond to climate change, we hypothesized that local conditions would either shift towards or away from optimal for growth of juvenile Chinook and coho salmon, and that the magnitude of change would be generally proportional to a stream's air-water sensitivity. The lowland to glacial-influenced range of habitat conditions in this study is inclusive of anadromous habitat types found throughout the Gulf of Alaska catchment area, thus results identified in this study may offer some perspective for the broader region.

In Chapter 2 of this thesis we explored a methodological topic related to monitoring water temperature in remote anadromous streams. In-situ water temperature data in challenging-to-access anadromous streams has often been monitored at a sole site in the lower reach and used to roughly characterize upstream thermal conditions. Yet watersheds can exhibit substantial thermal heterogeneity that is essential for characterizing and managing habitat, underscoring the value of either a more extensive sensor array, high-resolution aerial imagery, or remote-sensing based temperature models. If none of these options are available, the extent to which lower-reach continuous temperature data is representative of upstream thermal conditions is not well characterized. We examined two years of continuous summer water temperatures from sensors throughout the three study tributaries previously described, representing a lowland-to-glacial geomorphic spectrum of the Kenai River drainage. Our results provided strategies for those planning to deploy or maintain a water temperature sensor array, and how the specific intended use of water temperature data will dictate the optimal monitoring strategy.

This project partially comprises the aquatic ecology component of the Southcentral Test Case, a multidisciplinary research effort funded by the National Science Foundation's Alaska Established Program to Stimulate Competitive Research (EPSCoR) program. The goal of the Southcentral Test Case aims to characterize the resiliency of social-ecological systems in the Kenai River watershed.

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# **Chapter 1. Landscape characteristics influence projected growth rates of stream-resident juvenile salmon in the face of climate change in the Kenai River watershed, southcentral Alaska<sup>1</sup>**

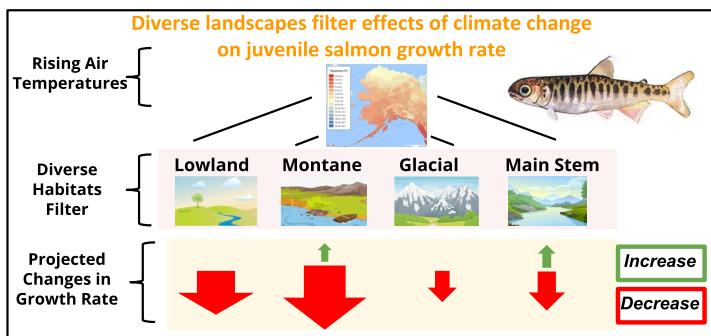
## **1.1 Abstract**

Climate change is affecting the distribution and productivity of Pacific salmon habitat throughout their range. At high latitudes, warmer temperatures have been associated with increased freshwater growth of juvenile salmon, but it is not clear how long this trend will continue before further warming leads to reduced growth. To explore the potential influence of climate warming on juvenile Chinook and coho salmon growth rates in southcentral Alaska, we coupled bioenergetics models with stream temperature sensitivity models for streams across the Kenai River watershed. We measured diet ( $n = 818$ ) and growth under current conditions and used published air temperature projections to model growth for the 2030-2039 and 2060-2069 decades. We estimated that direct effects of climate warming on juvenile growth (body mass at the end of the summer) will be primarily negative, ranging from +2.6% to -23.3% relative to a 2010-2019 baseline, depending on cohort, feeding rate, and climate scenario. Our results illustrate how a diversity of landscape settings is expected to produce variation in the magnitude of climate effects throughout juvenile salmon rearing habitats.

---

<sup>1</sup>Meyer, B.M., Wipflfi, M.S., Rinella, D.J., Schoen, E.S., Falke, J.A. Manuscript in prep for *Canadian Journal of Fisheries and Aquatic Sciences*.

### 1.1.1 Graphical Abstract



**Figure 1.1.1.** Growth rates of rearing juvenile Chinook and coho salmon in varied habitat settings respond differently to the influence of rising air temperatures.

## 1.2 Introduction

Climate change is driving shifts in water temperature regimes throughout the range of Pacific salmon (*Oncorhynchus* spp.), but effects on freshwater rearing habitat are context-specific and difficult to predict (Crozier and Zabel 2006; Schindler and Hilborn 2015; Wade et al. 2017). Even within Alaska, at the northern end of Pacific salmon distribution, increasing water temperature may be driving contractions in the distribution of thermally suitable rearing habitat in low-elevation, low-gradient drainages (Mauger et al. 2017) while simultaneously providing new opportunities for salmon in previously cold-limited areas (Schoen et al. 2017). Diverse landscapes can help mediate the effects of broader climate signals on anadromous habitat in ways that depend on local geography, thus ensuring a climate trend will have neither unidirectional or homogenous effects on the wider ecosystem (Schindler et al. 2008, Lynch et al. 2016).

Among stream-rearing Pacific salmon, growth rates of Chinook (*O. tshawytscha*) and coho (*O. kisutch*) salmon may be especially sensitive to shifts in freshwater thermal regimes as these fish reside in streams for up to two (for Chinook salmon) or three (for coho salmon) years before migrating to sea (Quinn 2005). Freshwater juvenile growth rate is relevant because insufficient gape size can limit ability of parr to consume energy-rich eggs from adult spawners (Armstrong et al. 2010). In addition, larger smolt size often correlates with better marine survival (Henderson and Cass 1991; Ruggerone et al. 2009; Scheuerell et

al. 2009) and can influence smolt outmigration timing, which in turn drives age structure and population stability (Cline et al. 2019). In subarctic regions of Alaska, warmer stream temperatures have been associated with increased juvenile growth of both Chinook (Falke et al. 2019) and coho salmon (e.g., Armstrong et al. 2010). However, it is unclear whether this pattern holds in more temperate regions with historically warmer thermal regimes, such as southcentral Alaska (Mauger et al. 2017; Shaftel et al. 2020), or how long it will persist before further warming leads to reduced growth.

Chinook salmon populations in the Kenai River (southcentral Alaska) have experienced declining productivity since 2005 (Fleischman and Reimer 2017), leading to harvest restrictions and closures as well as stimulating interest into past, present, and future drivers. To explore how juvenile Chinook and coho salmon growth rates may respond to rising air temperatures across the Kenai River watershed's diverse landscape, we measured water temperatures, juvenile salmon growth, and diet patterns in three geomorphically distinct sub-basins and in the main stem during the summer rearing periods of 2015 and 2016. We used these data to parameterize air-water sensitivity (Mohseni et al. 1999) and bioenergetics models (Deslauriers et al. 2017; Hanson 1997) to estimate changes in future growth under different climate and consumption scenarios. Fish bioenergetics models describe growth as a function of temperature and food ration and do not include other biological factors (stream productivity, predation, disease, and competition) and physical factors (flow regime (Poff et al. 1997), water quality, and habitat connectivity) that affect fish growth, but allow for modeling changing habitat conditions that are otherwise difficult to address. To address the uncertainty of future conditions we used a suite of climate and feeding rate scenarios for simulation inputs. Our approach allowed us to estimate of change in mass at the end of the growing season under possible scenarios. We anticipated that the three geomorphically-distinct focal tributaries and main stem would each exhibit unique thermal regimes and feeding rate patterns and that juvenile Chinook and coho salmon populations in each will/would display distinct patterns in juvenile growth rates attributable in part to thermal differences.

Our broader goals were to illustrate how diverse landscapes “filter” the effects of climate change (Griffiths et al. 2014) on juvenile Chinook and coho salmon rearing habitat, characterize how juvenile growth rates respond differentially to a common climate signal, and to project how these differential responses may influence future growth. Our specific objectives were: a) to characterize feeding rates and thermal conditions that contribute to differences in current growth rates, and b.) to use growth simulations to identify the feeding rate and thermal conditions that influence response of juvenile growth rate to future climate scenarios. By identifying spatial and temporal patterns in variables that influence growth in nearby yet distinct habitats we aimed to better understand how juvenile salmon productivity may respond to climate change.

### **1.3 Materials & Methods**

#### **1.3.1 Summary**

We measured air temperature, water temperature, and the growth rates and diet composition of juvenile Chinook and coho salmon during 2015 and 2016 throughout the Kenai River watershed. Based on these field data, we simulated juvenile growth during summer under current conditions using coupled stream temperature models and bioenergetic models. We then compared the relative changes in growth from a 2010-2019 baseline period to those projected under various future temperature and feeding rate scenarios for the 2030-2039 and 2060-2069 decades. The stream temperature model generated monthly stream temperatures which were input as daily values to a standard bioenergetic model that predicted daily growth rate and size of idealized juvenile Chinook or coho salmon. Our model used field-based empirical inputs for food, temperature, and fish size across geographically diverse cohorts within the Kenai River watershed, emphasizing the diversity of food and water temperature conditions across space and time.

### **1.3.2 Study Area**

The Kenai River drains an area of 5568 km<sup>2</sup> in southcentral Alaska, running 182 kilometers west from the Kenai Mountains and emptying into Cook Inlet near the city of Kenai (Figure 1.1). The watershed supports some of Alaska's most intensively managed and harvested salmon populations, including commercial, sport, subsistence, and personal-use fisheries (Franklin et al. 2019). We conducted field sampling in three tributaries of the Kenai River in 2015 and 2016: Beaver Creek (lowland), Russian River (montane), and Ptarmigan Creek (glacial), and the Kenai River main stem (Table 1.1). The lowland tributary is characterized as low-elevation (21 - 65 m) and low-gradient, dominated by wetlands. The resulting longer water residence time coupled with early-season snowmelt was anticipated to produce higher average water temperatures and result in high sensitivity to air temperature (Wells and Toniolo 2018; Mauger et al. 2017). In contrast, the glacial tributary is characterized as high-elevation (166 - 1000 m) high-gradient, and lightly glacially-influenced. The resulting low water residence time (e.g., time that water spends traveling through a catchment) coupled with late-season snowmelt and glacial melt throughout the summer was anticipated to produce lower average water temperatures and lower sensitivity to air temperature. The montane tributary represented an intermediate in all of these attributes. The geography of the Kenai River watershed encompasses the range of watershed types found throughout the Gulf of Alaska catchment area (Snyder 2016), thus results gained from this study may be relevant to the broader region.

### **1.3.3 Field Sampling**

#### *Stream Temperature*

We acquired water and air temperature data from an array of HOBO® Temp Pro v2 loggers deployed during summers 2015 and 2016, USGS stream gauge stations at Soldotna and Cooper Landing, and National Weather Service archives for the Kenai Airport. Water and air temperature data were collected at a minimum of three sites per tributary and two sites in the main stem along a longitudinal gradient from lower to upper reaches. We employed best practices and standards for collection of temperature time series as described in Mauger et

al. (2015). Appendix 1.2 describes site locations, methods used to ensure sites were representative of local environs, and equipment calibration and check procedures.

#### *Juvenile Salmon Capture*

We sampled juvenile Chinook and coho salmon ( $n = 4,275$ ) within the lower, middle, and upper extent of their documented habitat (Blossom and Johnson 2017; Reimer 2013) in each of the three focal tributaries (Figure 1.1). We also sampled sites in the mainstem Kenai River near the mouths of Beaver Creek and the Russian River. Exploratory sampling did not capture target species in lentic environments above or below Ptarmigan Creek (Ptarmigan Lake and Kenai Lake, respectively) thus we did not include these sampling sites. Fish sampling efforts at each site were constrained to a 200-m length of stream centered around the nearest water temperature logger site, but sampling location was modified if fish capture success was low or terrain prevented access. We sampled fish from main channel and off-channel habitat at each site. Sites were visited approximately monthly ( $31 \pm 5$  days, mean  $\pm$  SD) throughout May – August 2015 and May – September 2016 (summarized in Appendix 1.1, Figure 1.1A). Coordinates for the fish sampling sites are listed in the supplementary information (Table 1.1S). At each fish sampling event we used a handheld YSI® 556 Multi-parameter instrument or Cooper-Atkins AquaTuff Instant Read® thermocouple to record water quality data (pH, conductivity ( $\mu\text{S}$ ), temperature ( $^{\circ}\text{C}$ )). We recorded site coordinates with a handheld.

We used egg-baited Gee® minnow traps to capture juvenile salmon, an effective method for passive capture of juvenile salmonids in pools and moving water in Alaska (Bryant 2009; Magnus 2006; Sethi and Benolkin 2013). We suspended 12 – 20 traps at water depths of 15 – 45 cm, taking measures to ensure sites were undisturbed by foot traffic prior to and during trap deployment so as not to alter the community of invertebrates normally available as juvenile salmon prey. We set the traps for 2-4 hours per set. We ensured that all salmon eggs used as bait were commercially sterilized or disinfected with a 10-minute

soak in a 1/100 Betadyne solution prior to use.

We anesthetized captured juvenile salmon prior to measurement and diet sampling by submersion in a 20-40 mg/L eugenol (AQUI-S™) bath for 2 to 3 minutes (Bowker et al. 2016). Once an individual exhibited a total loss of equilibrium, we removed them from the bath and measured fork length (snout tip to terminus of middle caudal fin rays) to the nearest 1 mm using a measuring board, then weighed them to the nearest 0.1 g with an electronic digital scale. We allowed fish to recover in aerated water until equilibrium was fully regained and retained them in-stream in a 3-mm mesh basket to prevent same-day recaptures. We identified and recorded all non-target fish species (e.g., slimy sculpin; *Cottus cognatus*, rainbow trout; *O. mykiss*) and transferred them to the holding basket without additional handling. We released all fish near the point of capture when daily sampling was complete.

For a subset of juvenile Chinook and coho salmon ( $n = 818$ ) we sampled scales and stomach contents to determine age and diet composition for bioenergetics models. At each monthly site visit we aimed to sample up to 16 juvenile Chinook and 16 coho salmon with fork lengths  $\geq 50$  mm, but sometimes fewer fish were sampled when abundance was low (Supplementary information Table 1.2S). We randomly selected fish  $\geq 50$  mm fork length in the field and cleared their guts by gently feeding water into their stomachs using a modified syringe (Culp et al. 1988). Stomach contents were flushed out of the mouth using gastric lavage technique (Foster 1977) into a 250  $\mu\text{m}$  sieve, then preserved in a minimum of 70% ethanol in a Whirl-Pak bag.

#### *Juvenile Salmon Age and Growth*

To estimate fish age, we aged scales from the same fish that were also selected for stomach content analysis and used this information to assign ages to the larger sample population (Quist et al. 2012). Methods for ageing scales and predicting age cohort for salmon without aged scales are outlined in Appendix 1.3.

We quantified the growth of juvenile salmon in sampling strata with adequate sample sizes of stream-rearing parr. We excluded age 2 coho salmon

and age 1 Chinook salmon from our analyses as these cohorts were anticipated to be almost exclusively pre-smolt outmigrants. Sample size for juvenile Chinook and coho salmon was variable across sampling events (range = 1 – 168 individuals per species/age cohort), due in part to the patchy distribution of fish across the landscape. We excluded iterations of  $n < 3$  observations when segregated by age, species, and sample event. We also excluded cases where the mean fish weight declined between sampling events, suggesting outmigration of larger individuals (2 of 55 cases). After applying these inclusion standards 72% (108/150) of the total possible combinations of sample event, age, and species remained.

We examined the temporal and spatial scales at which fish growth patterns could be segregated and compared. First, we explored the possibility of grouping and averaging data from sites within each study watershed. We observed significant differences in daily mean temperature (June 1 – Aug 20) among sites within two of the four watersheds (the montane and main stem) ( $p < 0.05$ , Kruskal-Wallis) and elected to retain all sites as segregated locations in further analyses.

To select an appropriate growth metric we created three linear mixed effect regression models, each with a unique metric of growth as the response (individual fish weight, specific growth rate, and weight at end of summer or “final weight”) and fit a relationship with its possible fixed (fish age, species, year, day or sampling event) and random (sampling site) variables. Final weight was defined as mean weight on August 6<sup>th</sup> (the earliest day for a final site visit among both years and all sites); final weight was estimated via linear interpolation when necessary. Final weight was the best-explained response by these predictors ( $R^2_{adj} = 0.86$ ) and was selected as the response metric for which to compare among future scenarios. We investigated if basic thermal metrics from June 1<sup>st</sup> – Aug 6<sup>th</sup> (mean, minimum, maximum, and sum of temperature values observed  $>15^\circ\text{C}$ , the approximate temperature at which juvenile salmon growth rates decline (Richter and Kolmes 2005)) were associated with final size at the scale of individual cohort (i.e. a unique fish age, species, and sampling site) and year.

See Appendix 1.4 for further details on linear mixed modeling methods and results.

### *Juvenile Salmon Diet*

We examined stomach content samples under 4.0x dissecting microscopes. Distinguishable invertebrates ( $n = 8879$ ) were identified to Family level or the lowest taxa feasible ( $n = 112$  taxon / life stage combinations identified) (Merritt and Cummins 1996) and body lengths were measured to the nearest 1.0 mm. We estimated lengths of partially digested prey based on intact individuals of the same taxon that appeared similar in size (Wipfli 1997). We assumed that the head and thorax represent 1/3 of the total length of partially digested prey (Gonzales 2006). Diet items that we could not use to positively assign ingestion of prey (e.g. exoskeletons, separated insect wings or legs, empty trichoptera casings, and head capsules unidentified to genus) were recorded but not included in diet proportions.

We characterized diet proportions in terms of mass, the most applicable metric for energy flow and food web studies (Chipps and Garvey 2007). We determined dry mass of individual invertebrates using the allometric formula

$$(1) \quad W = aL^b$$

where  $W$  is the total dry body mass,  $L$  is the total body length, and  $a$  and  $b$  are constants (Ricker 1973). We derived length–mass regression constants  $a$  and  $b$  and percent dry mass values from a database of over 100 genera with values published in existing literature and from Alaskan stream invertebrates. For prey items of juvenile *Oncorhynchus* spp. we used length–weight relationships developed from fish captured in this study (B.E. Meyer, unpublished data). We summarized diet composition using the following six categories: 1) aquatic invertebrates of aquatic origin, 2) terrestrial invertebrates, 3) terrestrial invertebrates of aquatic origin, 4) salmon eggs, 5) fish eggs (inclusive of all non-salmon species), 6) invertebrates of unknown origin. We assigned energy density

values to the six prey item categories using literature references (Table 1.2) for use in bioenergetics modeling.

### **1.3.4 Projected Future Trends in Water Temperature and Salmon Growth Summary**

To characterize how climate change-driven shifts in air temperature regimes may affect juvenile Chinook and coho salmon growth rates, we coupled air-water temperature sensitivity models with bioenergetics models. Bioenergetics model output is best suited for making relative comparisons rather than precise quantitative predictions (Ney 1993), so to address the uncertainty of future conditions we used a suite of climate and feeding rate scenarios for simulation inputs.

We used a two-step modeling approach (Figure 1.2). First, we estimated salmon feeding rates under current conditions, based on our observed data. Second, we projected future growth rates based on alternative scenarios of climate warming and prey consumption, scaled relative to current feeding rates. Our approach allowed us to estimate of change in salmon parr body mass at end of the growing season under different future scenarios. See supplementary information Section 1.1S *The Wisconsin Bioenergetics Model* (Hanson 1997) for further details on bioenergetics modeling.

#### *Stream Temperature*

We used published projections of air temperature along with our field data on air and water temperature to estimate future water temperatures for use in bioenergetics simulations. We calculated air-water sensitivity ( $\Delta^{\circ}\text{C } T_w / ^{\circ}\text{C } T_a$ ), a metric quantifying the average change in stream temperature per 1 °C change in air temperature (Mohseni et al. 1999), for each water temperature logger site associated with a fish sampling site ( $n = 10$ ). We calculated weekly mean values of air and water temperature for each week of the 2015-2016 study periods that had < 30% of observations missing. We fit a linear regression for each site using the weekly mean values from both years. We used a linear relationship

because streams in colder climates like the Kenai Peninsula rarely experience temperatures ( $>20^{\circ}\text{C}$ ) where evaporative cooling effects flatten out the air-water temperature relationship (Mohseni et al. 1998). We selected weekly mean temperatures rather than a shorter time interval because weekly time scales allows for integration daily fluctuations in factors that influence temperature such as high precipitation or drought and generally produces better correlations (Erickson and Stefan 2000). We developed the sensitivity relationships from a period of days with observations common to all sites and years (June 1<sup>st</sup> to Aug. 20<sup>th</sup>), with the exception of the Lower Russian River site, for which earliest available water temperature data in 2015 was June 22<sup>nd</sup>.

For daily water temperature inputs in scenarios modeling, we used projected water temperatures derived from site-specific sensitivity relationships based on 2015-2016 field data. We used downscaled projections of mean monthly air temperatures as inputs following the linear formula

$$(2) \quad T_{\text{Water}} = m(T_{\text{Air}}) + b$$

where  $m$  and  $b$  are the site-specific slope and intercept values (Table 1.4S, supplementary data). We used monthly decadal mean downscaled air temperatures published by Scenarios Network for Arctic and Alaska Planning (SNAP) (2014) based on the mean of the five best-performing global climate models for Alaska (Walsh et al. 2008) as daily input values for the periods of May – September 2010-2019, 2030-2039, and 2060-2069 under the RCP 6.0 (mid-range CO<sub>2</sub> emissions) and RCP 8.5 (rapid increase CO<sub>2</sub> emissions) scenarios. We regressed mean monthly water temperatures observed in the 2015-2016 field season against those predicted for the same time period by each model using SNAP inputs to investigate performance of the stream temperature models.

#### *Projected Juvenile Salmon Growth*

We used a two-step modeling process to estimate projected effects of shifting water temperature regime on juvenile salmon growth. First, we modeled

salmon growth and consumption under current conditions using field data from 2015-2016 as inputs. We performed a simulation for each cohort (e.g. unique iteration of sampling site, fish species, and fish age) fit to mean start and final weight for intervals between sequential site visits throughout the summer growing season. we summarized diet composition inputs in terms of mean proportion by weight of each diet item category (Table 1.2). We calculated diet proportions segregated at the scale of watershed, age, and species while pooling samples across individual sites, years, and sampling events. We used the coarser spatiotemporal scale for diet inputs because gastric lavage samples provide a “snapshot” of diet intake, and pooling diet samples reduces the influence of random variability on diet composition model inputs. For daily food inputs, simulations used constant diet proportions and energy density values throughout each simulation. The output of these simulations was an estimated feeding rate, expressed in terms of a proportion (*p*-value) of the theoretical maximum consumption rate under the observed conditions (Jobling 1994).

Second, we simulated salmon growth rates under a range of potential future scenarios of climate warming and feeding rates. We used the resultant feeding rates from the simulations of current conditions to generate three feeding-rate scenarios per cohort for modeling future growth (see supplementary information Table 1.3S for complete results). The three rates we used to fit simulations included a.) the mean feeding rate under current conditions, b.) +20% of mean feeding rate, and c.) -20% of mean feeding rate, intended to represent low, medium, and high feeding rate scenarios.

Future salmon growth was projected from May 26<sup>th</sup> to Sept 4<sup>th</sup>. The start date was the earliest day of available fish weight data common to all sites and fieldwork years and the end date was calculated as the earliest final fish sampling event (August 6<sup>th</sup>) plus an additional 30 days to include the remaining summer season. Starting weight for each scenario simulation was the mean weight (either observed or linearly interpolated) on May 26<sup>th</sup> from the simulations of current conditions.

We estimated the direct effects of climate warming on growth in terms of the percent change in final body weight, relative to the 2010-2019 simulations (Table 1.4). We used the Fishbioenergetics 4.0 R Shiny app (Deslauriers et al. 2017) to perform a total of 378 unique growth simulations (21 cohorts x 2 climate scenarios x 3 feeding rate scenarios x 3 decadal periods). We used Stewart and Ibarra's (1991) bioenergetics parameter values for both species, which were adapted for Chinook salmon from a bioenergetics model for coho salmon. Although these parameters were originally calibrated for adult fish, they have accurately predicted juvenile Chinook salmon growth in laboratory and field settings (Madenjian et al. 2004). Plumb and Moffitt (2015) found that Stewart and Ibarra's (1991) parameters overestimate the metabolic consequences of higher temperatures on sub-yearling Chinook salmon, so recent studies have employed modified temperature-dependent consumption parameters for both species when simulation temperatures were >18°C to minimize parameter error (Davis et al. 2019). However, none of the daily water temperature inputs in our simulations were >18°C, thus the Stewart and Ibarra (1991) parameters were employed for all simulations. Previous efforts with bioenergetics modeling with Alaskan juvenile Chinook salmon found the Stewart and Ibarra (1991) parameters better suited to describe growth than the Plumb and Moffit (2015) parameters (Falke et al. 2019).

We verified that our response variable, simulated mean weight at August 6<sup>th</sup>, corresponded with observed or linearly interpolated values (Simulated Mean Weight = 0.39 + 0.97(Observed Mean Weight),  $r^2 = 0.9$ ).

## 1.4 Results

### 1.4.1 Fish Capture

Age 0 juvenile Chinook salmon and age 0 as well as 1 coho salmon were captured throughout the three study tributaries and main stem of the Kenai River (Table 1.3). Juvenile Chinook salmon were relatively sparse compared to juvenile coho salmon in all three tributaries, but were more common in the main stem (Supplementary information Table 1.2S.)

## **1.4.2 Water Temperature**

### *Observed Water Temperatures*

Observed water temperatures ranged from 5.3°C – 19.6°C with a mean  $\pm$  SD of 12.3°C  $\pm$  2.2°C during the set of days with data common to both years of field data (June 1 – August 20) (Figure 1.3). Overall, the montane drainage sites had the highest mean water temperature (13.3  $\pm$  2.4°C, mean  $\pm$  SD), followed by the lowland (12.6  $\pm$  1.7°C, mean  $\pm$  SD), glacial (11.8  $\pm$  1.6°C, mean  $\pm$  SD), and mainstem (11.1  $\pm$  2.4°C, mean  $\pm$  SD) drainages. Instantaneous temperature exceeded 15°C at all sites at least once, though daily mean exceeded 15°C only at the middle and upper montane sites. Mean water temperatures across all sites were not consistently higher or lower in 2015 than in 2016.

### *Observed Air-Water Sensitivities*

Sites with higher air-water sensitivities (slopes of air-water temperature relationship) generally had more predictive relationships (higher  $r^2$  values) between observed air and water temperature ( $n = 10$  sites, coefficient of determination =  $-0.08 + 0.83 \times \text{Sensitivity}$ ,  $r^2 = 0.47$ ,  $p < 0.05$ ). The glacial watershed exhibited notably lower air-water sensitivity and correlation than the other watersheds, which were generally higher but variable (Figure 1.4). Sensitivity values ranged from 0.64 – 0.74 in the lowland watershed, 0.45 – 0.67 in the montane watershed, 0.20 – 0.32 in the glacial watershed, and 0.68 – 0.72 in the main stem. Correlation values ranged from 0.61 – 0.70 in the lowland watershed, 0.19 – 0.48 in the montane watershed, 0.04 – 0.17 in the glacial watershed, and 0.20 – 0.35 in the main stem. Linear model parameters for regressions used to estimate air-water sensitivity at each site are reported in supplementary information (Table 1.4S).

### *Projected Water Temperatures*

Projected water temperatures output from air-water temperature sensitivity models for the 2010-2019 decade ranged 6.2°C – 15.3°C, mean  $\pm$  SD = 11.1  $\pm$  1.9 °C (Figure 1.5). The greater range of values in the observed water

temperatures relative to the projected arose from the difference in temporal scale of the two datasets, with observed water temperature measurements made at 15-minute intervals while projected water temperatures were monthly decadal means.

Projected water temperatures generated using the 2010-2019 decadal mean air temperature inputs showed minimal systematic difference from the observed 2015-2016 summer water temperatures, with an overall mean absolute difference of  $0.3 \pm 1.22^{\circ}\text{C}$  (mean  $\pm$  SD). Correlations between projected and observed month mean water temperatures ranged from  $r^2 = 0.22 - 0.95$ . Mean projected monthly water temperature differed only slightly between the mid-range and rapid-increase scenarios (absolute difference =  $0.2 \pm 0.0^{\circ}\text{C}$ , mean  $\pm$  SD).

Projected water temperatures increased by a greater magnitude under the rapid-increase climate scenario than under the mid-range scenario at all sites (Figure 1.6). Under the rapid-increase emissions scenario mean change in water temperature relative to 2010-2019 ranged  $0.2^{\circ}\text{C} - 1.8^{\circ}\text{C}$  among sites and decades, while under the mid-range emission scenario the range was  $0.1^{\circ}\text{C} - 1.1^{\circ}\text{C}$ . The magnitude of projected change under future climate scenarios was generally smallest in the glacial watershed and largest in the main stem and lowland watersheds (Figure 1.6).

#### **1.4.3 Juvenile Salmon Diet**

A total of 13,723 individual items were identified from 818 diet samples. Among the 11,983 diet items recognizable as individual organisms, 8,879 of them were identifiable as specific taxa with the remainder assigned as "Unknown Invertebrate" without a dry mass estimate or assigned energy value.

Diet composition varied among cohorts and watersheds. Terrestrial and marine subsidies (terrestrial invertebrates and salmon eggs) composed >50% of the overall diet by dry mass in nine of 12 iterations of watershed, species, and age (averaged between both years, Figure 1.7). Fish smaller than 60 mm FL did not consume salmon eggs or unidentified fish eggs, consistent with a gape limit for juvenile salmon for large diet items observed in other populations (Armstrong et al. 2010).

#### **1.4.4 Observed Juvenile Salmon Growth**

The final size of salmon parr (mass at August 6<sup>th</sup>) by age and species varied markedly across sites and years. Final sizes of age-0 Chinook salmon populations varied by 184% among sites and years, age-0 coho salmon varied by 242%, and age-1 coho salmon by 108% (Figure 1.8). Individual watersheds were not consistently associated with the highest or lowest final size but instead age, species, and year accounted for larger differences (Figure 1.8). Basic thermal metrics (mean, maximum, and minimum temperature, and sum of all 0.25-hourly temperature observations >15°C) were not predictive of final size (all  $r^2 < 0.01$ ).

#### **1.4.5 Projected Juvenile Salmon Growth Under Future Scenarios**

The projected growth response of juvenile salmon to climate warming was negative in almost all cases, ranging from +2.6% to -23.3% among decades across cohorts, feeding rate scenarios, and climate scenarios (Figure 1.9). All cohorts saw a decrease in final mass under at least one future scenario relative to the 2010-2019 simulations, and three cohorts (of 21 total) exhibited at least one future scenario in which fish mass increased (Table 1.3). For most cohorts, increased feeding rate (+20%) scenarios generally produced a smaller magnitude of response relative to low feeding rate scenarios (-20%).

### **1.5 Discussion**

#### **1.5.1 Overall**

Juvenile salmon mass at end of summer was projected to decline by the 2030s and 2060s relative to the 2010-2019 time period under most climate and feeding rate scenarios modeled in this study. These results suggest climate warming over the next 10-50 years will reduce juvenile Chinook and coho salmon growth rates across a wide diversity of habitat types, even if salmon substantially increase their feeding rates. No existing models can predict the responses of complex systems to climate change with any certainty (Schindler and Hilborn 2015); instead, our approach was to project the likely responses of salmon among distinct environments to plausible future climate scenarios.

## **1.5.2 Temperature Effects**

### *Observed Water Temperatures*

We observed a wide diversity of summer thermal regimes throughout the Kenai River watershed. The range of summer temperatures observed in our study were intermediate relative to other well-studied salmon bearing systems such as the warmer Columbia River system (Chang and Psaris 2013) or generally cooler Bristol Bay systems (Lisi et al. 2013). The Kenai River watershed exhibits a range of physiography similar to the nearby Matanuska-Susitna basin to the north, and the range of temperatures observed in the two regions were similar (Shaftel et al. 2020). Surprisingly, our montane tributary was on average slightly warmer than the lowland system, though this could be an artifact of specific site locations rather than overall means throughout the watersheds; a more detailed reach-scale spatial statistical network model (Isaak et al. 2014) for the region currently in development (Jones 2019) will reveal more detailed stream temperature patterns throughout the region. The glacial tributary in our study was generally warmer than other glacial systems studied in southeast Alaska (Fellman et al. 2014), which could be attributable to warming effects of the large lake upstream of our sampling sites (Lisi et al. 2013).

### *Projected Future Water Temperatures*

Monthly mean water temperature in future time periods saw increases proportional to site-specific sensitivity values, with both sensitivity and air-water temperature correlation generally decreasing with increasing stream gradient and glacial influence. Our models accounted for 23% – 94% of the variability in water temperature in hindcasted data, with lower accuracy at higher-elevation sites consistent with previous work in the region (Mauger et al. 2017). Our projected increases in water temperature throughout the Kenai River watershed are consistent with those projected for the nearby Matanuska-Susitna basin (Shaftel et al. 2020), where climate change projections for 2060–2069 indicated a future shift toward warm thermal regimes and a reduced portfolio of thermal diversity.

While correlation values are lower at some of our study sites, the predicted temperatures were overall close to the observed values in terms of mean difference ( $0.30 \pm 1.22^{\circ}\text{C}$ , mean  $\pm$  SD). In our model temperatures are used for simulating long-term trends in salmon growth across decades rather than in a particular month, thus temperature projections that do not precisely match month-to-month observed temperatures are acceptable as model inputs. Some caveats on using monthly temperature projections to simulate daily input values should be noted. For example, it may mask the effect of weather patterns such as a dry period resulting in warmer water temperatures until precipitation arrives. The projected future water temperatures employed as bioenergetics inputs in this study are best interpreted as potential scenarios rather than deterministic predictions. Future research that incorporates models addressing the non-stationarity (Milly et al. 2008) of seasonal, annual, and decadal factors that influence air-water sensitivity could offer closer estimates of future water temperatures. Processes that shift the proportions of a watershed's input sources such as drying wetlands (Klein et al. 2005), shifts in precipitation trends (SNAP 2014), or glacial retreat (Bliss et al. 2014) will be of consequence in long-term changes in sensitivity relationships.

A more complete understanding of the relationship between warming air temperatures and their effect on stream temperatures would account for a suite of factors beyond the scope of this study including glacial and snow melt (Cline 2020), interaction with groundwater, flow and discharge rates, solar radiation, wind, and humidity (Arismendi et al. 2014). For example the model employed here does not incorporate the potential effect of future changes in ice melt on water temperature regime in the glacial watershed. Fellman et al. (2014) found that Southeast Alaska watersheds with >30% glacier coverage generally saw seasonal cooling in summer thermal regimes driven by glacial melt, while watersheds with <30% glacial coverage saw summertime warming in spite of the glacial melt. The two glacial-influenced watersheds in this study (Ptarmigan Creek and Kenai River, 7% and 14% ice coverage respectively) are well below 30% glacial coverage (Fig. 1.1). Additionally, most small Alaskan glaciers are

seeing declines in runoff as they have already decreased past peak potential for meltwater runoff (Bliss et al. 2014). Thus, while glacial melt will likely moderate the influence of warming air temperatures, cooling thermal summer regimes are an unlikely outcome of ongoing climate warming in this system.

### **1.5.3 Juvenile Salmon Growth Under Future Warming Scenarios**

Juvenile Chinook and coho salmon growth responded primarily in a negative direction to increased future water temperatures despite simulated increases in feeding rates. Response to future scenarios varied by geomorphic setting and among cohorts in proportion to the magnitude of change in water temperature. Simulated final size at the end of the growing season (Sept. 4<sup>th</sup>) decreased in future decades in nearly all climate and feeding rate scenarios. In our simulations water temperature was the sole environmental variable altered in future time periods, thus a scenario resulting in a net decrease of growth relative to 2010-2019 outcomes implies a greater proportion of days with mean water temperature further away from the cohort's optimal temperature (generally ranging from 12°C - 17°C (Richter and Kolmes 2005)). The water temperature threshold value at which juvenile Chinook and coho salmon growth rate begins decreasing depends both on fish mass and feeding rate (Beauchamp et al. 2007) and is not fixed across space and time. To our knowledge, our study is unique in that simulations incorporate observed fish size and feeding rate data from a diverse selection of cohorts and environments, emphasizing the heterogenous response of a temperature-dependent process across diverse landscapes.

Our results differ from some other studies modeling the effect of rising water temperature on juvenile salmon growth. Fullerton et al. (2017) instead projected increasing growth rates for juvenile Chinook salmon under future warmer temperature regimes throughout a diverse set of simulated watersheds. The differing result may be partially attributable to their use of Plumb and Moffitt's (2015) bioenergetics parameters, which generally estimate higher temperature values for metabolic optimum, rather than the Stewart and Ibarra (1991) parameters employed here. Other modeling efforts by Beer and Anderson (2011), like our study, found results varying by ecoregion with rising mean temperature

contributing to increased growth in streams that presently experience cool temperatures but decreasing juvenile growth in already-warm streams.

Implications of our results would differ from those from other recent work in a cool tributary of the Yukon River, at the northern edge of the species range, which found increased growth of juvenile Chinook salmon under warmer conditions (Falke et al. 2019). Our results also differ from those observed in Bristol Bay (Cline et al. 2019) which found warming temperatures generally increased growth rates of juvenile sockeye salmon, resulting in earlier outmigration timing and contributing to a simplification of population age-class structure. In contrast, if growth decreases under future scenarios, smaller size could act as a cue to extend freshwater residency. It is possible the decreased growth rate trend in future decades modeled in our study could be counterbalanced to some degree by two future trends: a) longer growing seasons, with earlier ice-out dates and later freeze-up dates (Brown et al. 2018) and the resulting extended period of opportunity for growth, and b) increased productivity in invertebrate communities resulting in increased food abundance (Klobucar et al. 2018). Modeling future trends in these processes are beyond the scope of this work, although we represented a potential increase in invertebrate production with our increased feeding rate scenarios. In general, caution is warranted in use of simple physiological models as a mechanistic basis for projecting fish size under rising temperature scenarios (Lefevre et al. 2018), however, our results support an expectation of reduced growth across a variety of plausible future conditions.

Chinook and coho salmon have different life histories and differential impacts associated with climate change are anticipated as a result. Juvenile Chinook salmon typically spend one summer in freshwater prior to outmigration as age 0 smolts, whereas juvenile coho salmon remain in freshwater for one to three years (Quinn 2005). If a shift in growth rates associated with climate change has effects on age class structure and migration timing as observed for Bristol Bay sockeye populations (Cline et al. 2019), these effects may be more recognizable in coho salmon populations with their more variable life history than in Chinook salmon populations. As to whether age classes could be gained or lost is difficult

to predict, because in some watersheds body size plays a major role as a cue for smolt outmigration timing while in others additional physical and environmental factors such as stream discharge, photoperiod, and lunar cycle are more influential (Spence and Dick 2012). Data collection on smolt outmigration timing could be a valuable field effort to ongoing monitoring efforts to understand how climate change is affecting Kenai River salmon populations.

Recognizing limitations of bioenergetics-based approaches is important for their interpretation. Absent from the bioenergetics model are hydrodynamic effects including ways in which turbidity and water velocity affect drift feeding behavior and movement, competition with conspecifics, predation, and others. Habitat modeling approaches that incorporate both hydrodynamic, bioenergetics, and net energy intake approaches show promise in assessing habitat quality to help inform conservation management (Naman et al. 2019; Wall et al. 2016), including those that are remote-sensing based and spatially explicit (Carmichael 2019; Falke et al. 2019). A strength in our use of the bioenergetics model is that it allows estimates of growth using field-based estimates of food consumption and water temperature experience, incorporating data across a large and diverse watershed.

The degree to which juvenile Chinook and coho salmon in the Kenai River may be able to adapt to new thermal regimes is not well understood. In a study using juvenile Chinook salmon from Washington State, Konecki et al. (1995) suggests that population-specific differences in response to their critical thermal maximum arise from individual acclimation rather than local adaptation, and Rosenthal (2019) suggests in a broader meta-analysis this may be the case for growth rate optima as well. Muñoz et al. (2015) detected both genetic and plastic effects of thermal experience in juvenile Chinook salmon that could act to enhance cardiac capacity in warmer environments. Characterizing the ability of juvenile salmon physiology to adapt to thermal regimes will be a critical area of research as thermal habitats are reshuffled as a result of climate change.

#### **1.5.4 Management Implications**

Our understanding of the degree to which juvenile salmon may or may not be able to tolerate and adapt to climate change-induced shifts in their habitat has implications for future management decisions regarding anadromous fish habitat. Muñoz et al. (2015) argued that potential for physiological adaptation to maximum thermal tolerance in juvenile Chinook salmon is limited and thus without climate mitigation there is a high likelihood of loss of many wild populations in the 21<sup>st</sup> century. Our study among many others demonstrates that the magnitude of effects from warming thermal regimes will vary among populations and habitat types (Post et al. 2009, McCarthy 2009, Shaftel et al. 2020), and recognizing this diversity is important to accurately assess risks (Crozier and Zabel 2006). A diverse portfolio of habitat types and life histories among and within Pacific salmon populations may offer the most valuable buffer against habitat disruption by climate change, in which case conservation and restoration of anadromous habitat would be an essential management strategy to ensure long-term viability of wild salmon populations (Mantua et al. 2015).

Management plans that incorporate conservation of riparian vegetation and off-channel habitat may help to mitigate effects of rising stream temperatures. Previous modeling exercises have supported the idea that riparian and stream restoration can offset some effects of rising water temperatures (Justice et al. 2017). Additionally, intact riparian vegetation can increase salmonid prey availability in some cases (Ryan 2016), whereas invasive plants can reduce riparian-sourced prey abundance (Roon et al. 2016). Our analysis did not include simulations where feeding rate increased or decreased across time, but the lower magnitudes of change under higher feeding rate scenarios (Table 1.4) indicate that fish may be able to maintain higher growth rates under increasing temperatures if food ration is increased. Huntsman and Falke (2019) found evidence that juvenile Chinook salmon in the Chena River (Alaska) dispersed to warmer and more productive off-channel habitats as summer water temperature increased to take advantage of energetically favorable growth conditions, in terms of both prey and thermal environment. As mainstem habitats warm, however,

access to cooler off-channel or upstream habitats may be important to offset increased metabolic costs.

### **1.5.5 Conclusions**

Results from this study suggest that in most environments throughout the Kenai River watershed, climate change-driven temperature increases over the next twenty to fifty years will have negative direct effects on juvenile Chinook and coho salmon growth rates, particularly in watersheds also highly sensitive to air temperature. The effect on growth rates may be buffered to some degree in fish with high consumption rates, such as those with seasonal access to marine derived nutrients (Rinella et al. 2011). The consequences of these effects for overall population structure and productivity are not well characterized, but shifts in size distribution could affect life-history features such as smoltification phenology or feeding habits limited by gape size (e.g. consumption of salmon eggs). Reduced juvenile growth could also result in lower marine survival due to size-selective mortality, and this could potentially cause reduced population productivity of these stocks (Ruggerone et al. 2009).

A growing consensus suggests the intra-species life history diversity sustained throughout a large, diverse watershed may provide resilience against potential phenological mismatches driven by climate change (Carr-Harris Charmaine et al. 2018). Our results illustrate how landscape settings produce a diverse set of responses to climate change, emphasizing the value of conserving a heterogenous, interconnected portfolio of habitat types and the varied life histories they support (Justice et al. 2017; Schindler et al. 2010; Thompson et al. 2019).

Southcentral Alaska's anadromous fish habitat remains among the world's most productive. An enhanced understanding of characteristics that support high-quality freshwater rearing habitat and buffer it from rising air temperatures allows for better development of conservation priorities and management strategies. The environments that today serve as productive juvenile salmon rearing habitat may be different from those in the future as climate change and development transform the landscape, thus watershed management plans will benefit from recognizing

the ever-shifting nature of habitat. Management approaches that recognize potential “future” habitats may offer value for long-term persistence of wild salmon populations.

## **1.6 Acknowledgements**

This study was funded by the Alaska Established Program to Stimulate Competitive Research (Alaska EPSCoR) NSF award #OIA-1208927 with matching funds from the state of Alaska, and was completed in partial fulfillment of an M.S. degree in fisheries. Funding also came from the Institute of Arctic Biology Summer Graduate Research Award, the Nicholas Hughes Memorial Scholarship, and the University of Alaska Department of Biology and Wildlife. Administrative support was provided by the Alaska Cooperative Fish and Wildlife Research Unit, University of Alaska College of Fisheries and Ocean Sciences, and Institute of Arctic Biology. We followed IACUC approved protocols (#720490-4) and Alaska Department of Fish and Game Fish Use Permit requirements (SF2015-191 and SF2016-158) to ensure proper animal handling care and precautions. Technicians Emily Neideigh, Christina Mielke, and Mike Lunde provided substantial field and laboratory support. In-kind support was provided by regional NGOs Kenai Watershed Forum and Cook Inletkeeper as well as Kenai Peninsula College. Michael Lindgren with Scenarios Network for Alaska and Arctic Planning provided assistance in acquiring projected air temperature data. Thanks to volunteer local support in the Kenai area from John and Molly Messick and Dave and Kathy Wartinbee, to Zach Baer and Dr. Leslie Jones for GIS assistance, and numerous other volunteers. The findings and conclusions in this article are those of the author(s) and do not necessarily represent the views of the U.S. Fish and Wildlife Service. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government. Data used in this study is available from the KNB (Knowledge Network for Biocomplexity) repository at doi:10.5063/F1Q52MZF.

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## 1.8 Tables

**Table 1.1.** Table of landscape characteristic values for tributaries derived from USGS 1 m Digital Elevation Map (USGS 2016), overall Kenai River watershed values from Benke and Cushing (2005).

Watershed	Elevation at mouth (m)	% Ice Cover in Watershed	Meets with Main Stem of Kenai (km)	Average Gradient (%)	Water-shed Area (km <sup>2</sup> )	Total Length (km)
Lowland (Beaver Creek)	21	0%	17	2%	157	58
Montane (Russian River)	106	<1%	121	9%	163	90
Glacial (Ptarmigan Creek)	166	7%	165	14%	86	43
Main Stem (Kenai River)	0	14%	NA	23%	5200	132

**Table 1.2.** Diet proportion inputs used for bioenergetics scenarios modeling. Numerical values below prey categories are energy density (J/g) estimates from literature sources.

		Fish Eggs	Aquatic Invert of Aquatic Origin	Terrestrial Invert	Terrestrial Invert of Aquatic Origin	Unknown Invert	Salmon Eggs
		(5235, <i>Beauchamp et al. (1989)</i> )	(3365, <i>McCarthy et al. (2009)</i> )	(5250, <i>McCarthy et al. (2009)</i> )	(4225, <i>McCarthy et al. (2009)</i> )		(9000, <i>Armstrong (2010)</i> )
<hr/>							
Lowland (Beaver Creek)	Chnk	0	0	0.31	0.47	0.02	0
	Coho	0	0	0.44	0.48	0.06	0.02
	Coho	1	0.06	0.35	0.51	0.08	0
Montane (Russian River)	Chnk	0	0	0.14	0.14	0.04	0.67
	Coho	0	0.01	0.16	0.42	0.15	0.02
	Coho	1	0.07	0.25	0.5	0.14	0.03
Glacial (Ptar- migan Creek)	Chnk	0	0	0.76	0.23	0.01	0
	Coho	0	0	0.05	0.03	0.05	0.87
	Coho	1	0.17	0.35	0.28	0.18	0.03
Main Stem (Kenai River)	Chnk	0	0.05	0.43	0.3	0.22	0
	Coho	0	0	0.05	0.26	0.01	0.69
	Coho	1	0.09	0.64	0.08	0	0.19

"Chnk" = Chinook salmon

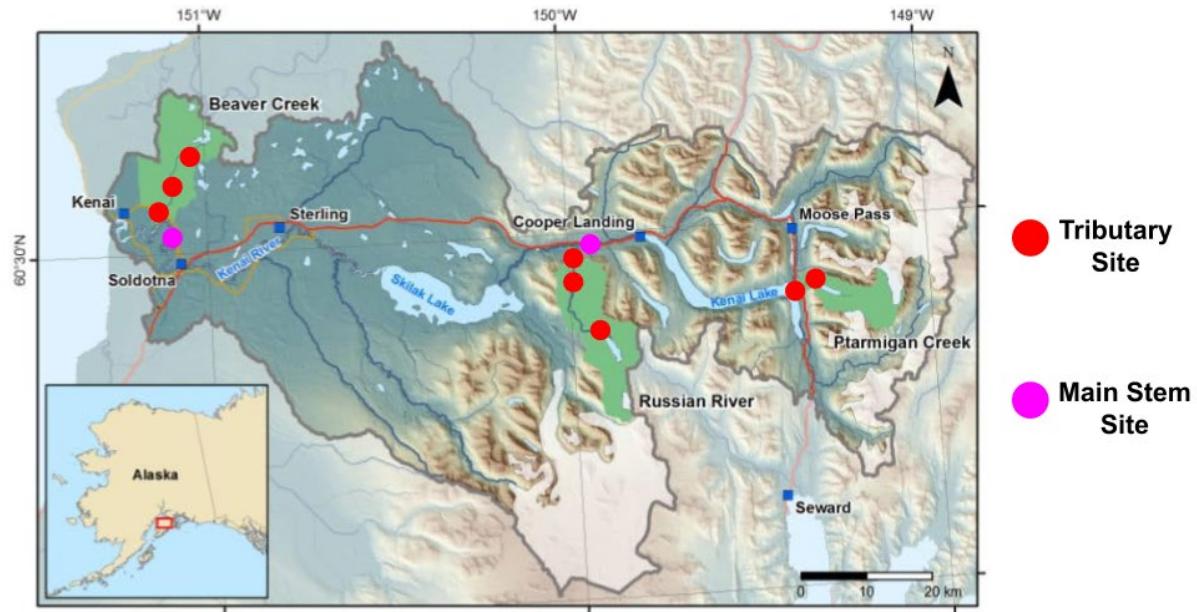
**Table 1.3.** Overall summary of fish size, weight, and length values (mean  $\pm$  SD). Coho salmon were captured in greater numbers than Chinook salmon in all watersheds except the mainstem Kenai River. The table summarizes overall catch results found in Table 1.S2 of supplementary information.

Watershed	Species	Age	Mean Fork Length (mm)	Mean Weight (g)	N
Lowland (Beaver Creek)	Chinook	0	54.3 $\pm$ 6.9	1.9 $\pm$ 0.8	203
	Coho	0	57.5 $\pm$ 10.1	2.3 $\pm$ 1.3	257
	Coho	1	82.2 $\pm$ 11.7	6.7 $\pm$ 2.8	1132
Montane (Russian River)	Chinook	0	56.2 $\pm$ 9.4	2.2 $\pm$ 1.1	102
	Coho	0	53.9 $\pm$ 7.8	1.9 $\pm$ 0.9	821
	Coho	1	77.4 $\pm$ 12.4	5.6 $\pm$ 2.7	219
Glacial (Ptarmigan Creek)	Chinook	0	70.9 $\pm$ 7.7	4.1 $\pm$ 1.2	30
	Coho	0	61.1 $\pm$ 8.4	2.6 $\pm$ 1.1	92
	Coho	1	82.6 $\pm$ 11.4	6.6 $\pm$ 2.8	292
Main Stem (Kenai River)	Chinook	0	55.8 $\pm$ 8.4	2.1 $\pm$ 0.9	840
	Coho	0	48.3 $\pm$ 4.9	1.3 $\pm$ 0.4	276
	Coho	1	79.6 $\pm$ 14.3	6.1 $\pm$ 3.1	11

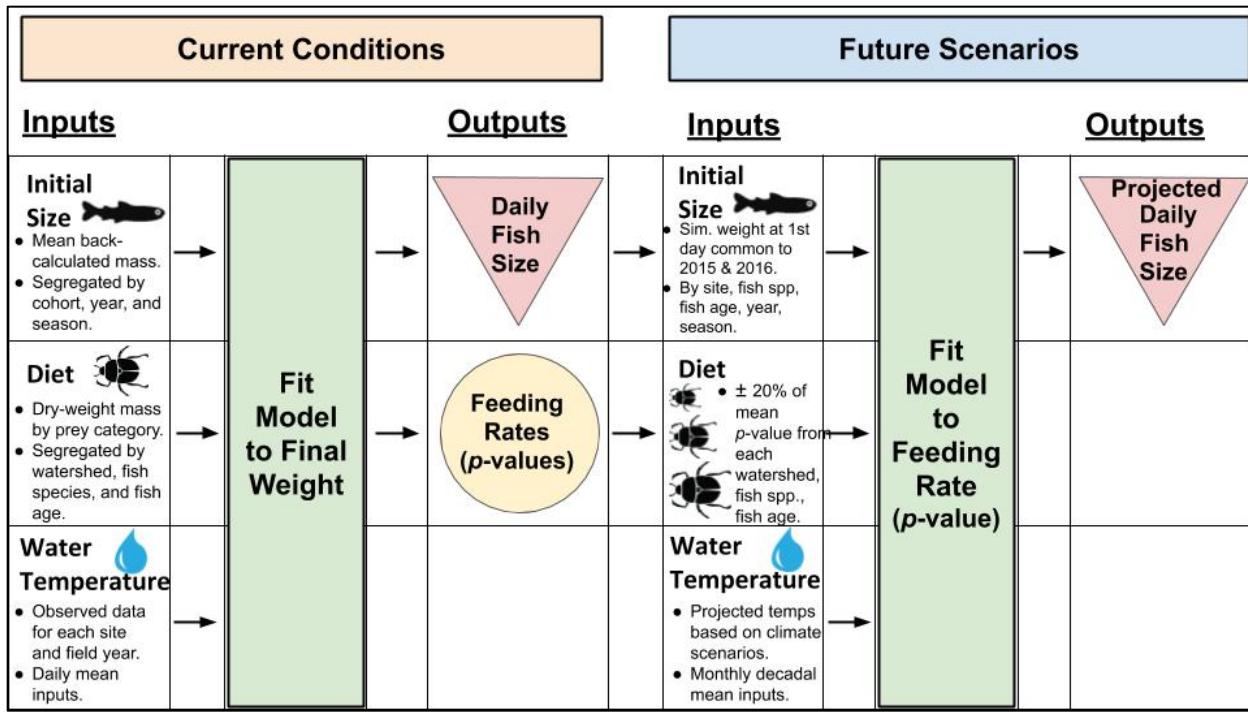
**Table 1.4** Percent change in final simulated fish mass relative to 2010-2019 scenario outcomes. Values are color scaled with red indicating shrinking fish mass (simulated weight at end of summer) and green for increasing size under future scenarios.

			RCP 6.0						RCP 8.5							
			2030-2039			2060-2069			2030-2039			2060-2069				
			P	-20%	Mean	20%	-20%	Mean	+20%	-20%	Mean	+20%	-20%	Mean	+20%	
Watershed	Reach	Population														
Lowland	Lower	Age 0 Chinook	-5.1	-4.3	-3.5	-11.5	-9.8	-8.2	-6.0	-4.8	-3.7	-19.5	-16.9	-14.6		
		Age 0 Coho	-5.5	-4.7	-4.0	-12.2	-10.6	-9.1	-6.5	-5.4	-4.3	-20.6	-18.1	-15.9		
		Age 1 Coho	-4.4	-3.6	-3.0	-9.8	-8.3	-7.0	-5.0	-4.0	-3.0	-16.8	-14.6	-12.6		
	Middle	Age 0 Chinook	-4.2	-3.4	-2.8	-9.1	-7.6	-6.2	-4.4	-3.4	-2.6	-15.3	-13.0	-11.0		
		Age 1 Coho	-3.5	-2.9	-2.3	-7.7	-6.4	-5.2	-3.7	-2.9	-2.1	-13.1	-11.2	-9.4		
	Upper	Age 0 Chinook	-4.5	-3.8	-3.1	-9.9	-8.5	-7.1	-5.0	-4.0	-3.2	-17.2	-15.1	-13.1		
		Age 1 Coho	-3.8	-3.2	-2.6	-8.5	-7.3	-6.1	-4.2	-3.3	-2.6	-15.0	-13.1	-11.3		
Montane	Lower	Age 0 Chinook	-0.5	0.1	0.5	-1.5	-0.4	0.5	-0.4	0.2	0.8	-3.3	-1.7	-0.2		
		Age 0 Coho	-1.3	-0.8	-0.3	-2.9	-1.9	-1.0	-1.4	-0.7	-0.2	-5.6	-4.0	-2.5		
		Age 1 Coho	-0.6	-0.1	0.4	-1.6	-0.6	0.2	-0.6	0.0	0.6	-3.4	-1.9	-0.5		
	Middle	Age 0 Coho	-7.7	-6.9	-6.2	-15.0	-13.6	-12.4	-8.2	-7.3	-6.6	-23.3	-21.3	-19.5		
		Age 1 Coho	-6.1	-5.5	-5.0	-12.1	-11.0	-10.0	-6.5	-5.8	-5.2	-19.0	-17.4	-16.0		
	Upper	Age 0 Coho	-5.2	-4.6	-4.1	-11.0	-9.9	-8.9	-5.7	-5.1	-4.5	-18.4	-16.8	-15.3		
		Age 1 Coho	-4.2	-3.7	-3.2	-9.0	-8.0	-7.1	-4.6	-4.0	-3.5	-15.3	-13.8	-12.4		
Glacial	Lower	Age 0 Chinook	-1.4	-1.1	-0.8	-3.0	-2.4	-1.9	-1.5	-1.1	-0.9	-5.1	-4.2	-3.4		
		Age 0 Coho	-2.0	-1.8	-1.5	-4.2	-3.7	-3.3	-2.1	-1.9	-1.6	-7.0	-6.2	-5.5		
		Age 1 Coho	-1.3	-1.1	-0.8	-2.9	-2.3	-1.8	-1.4	-1.1	-0.8	-4.8	-4.0	-3.2		
	Middle	Age 1 Coho	-0.8	-0.6	-0.5	-1.7	-1.4	-1.1	-0.8	-0.6	-0.5	-2.7	-2.2	-1.8		
	Main Stem	Lower	Age 0 Chinook	-3.6	-2.7	-2.0	-8.0	-6.3	-4.8	-3.8	-2.7	-1.7	-14.9	-12.3	-10.0	
		Age 0 Coho	-4.5	-3.7	-2.9	-9.9	-8.3	-6.8	-5.0	-3.9	-3.0	-17.8	-15.4	-13.1		
	Middle	Age 0 Chinook	0.1	1.0	1.9	-0.8	1.0	2.7	0.4	1.5	2.6	-3.2	-0.5	2.1		

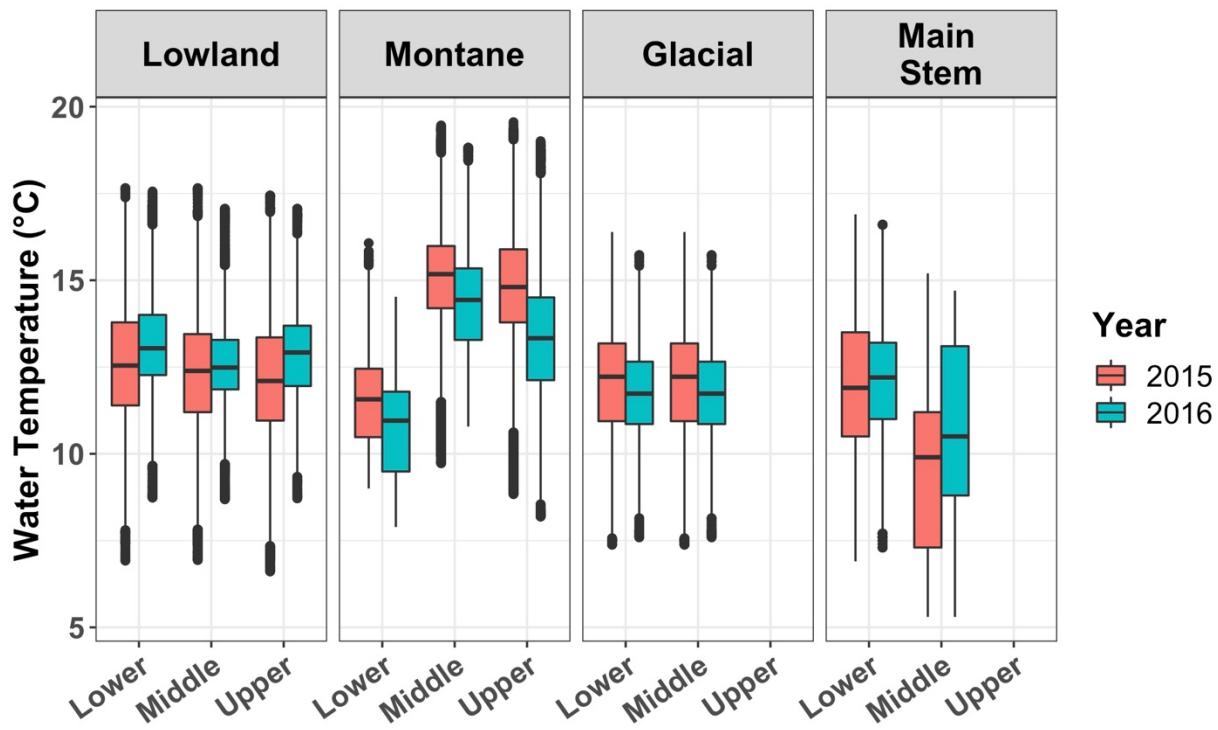
## 1.9 Figures



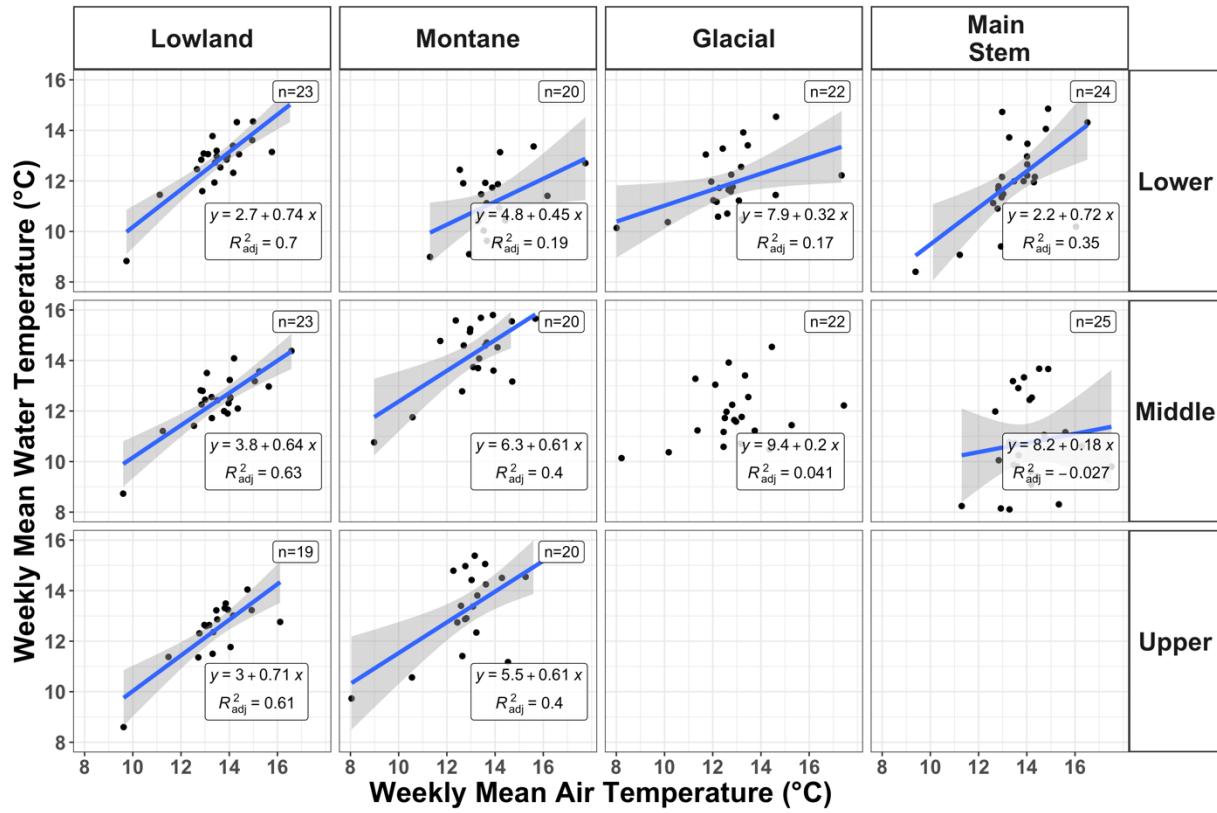
**Figure 1.1.** Kenai River watershed with study tributaries and fish sampling sites highlighted.  
Map modified from Schoen et al. 2017.



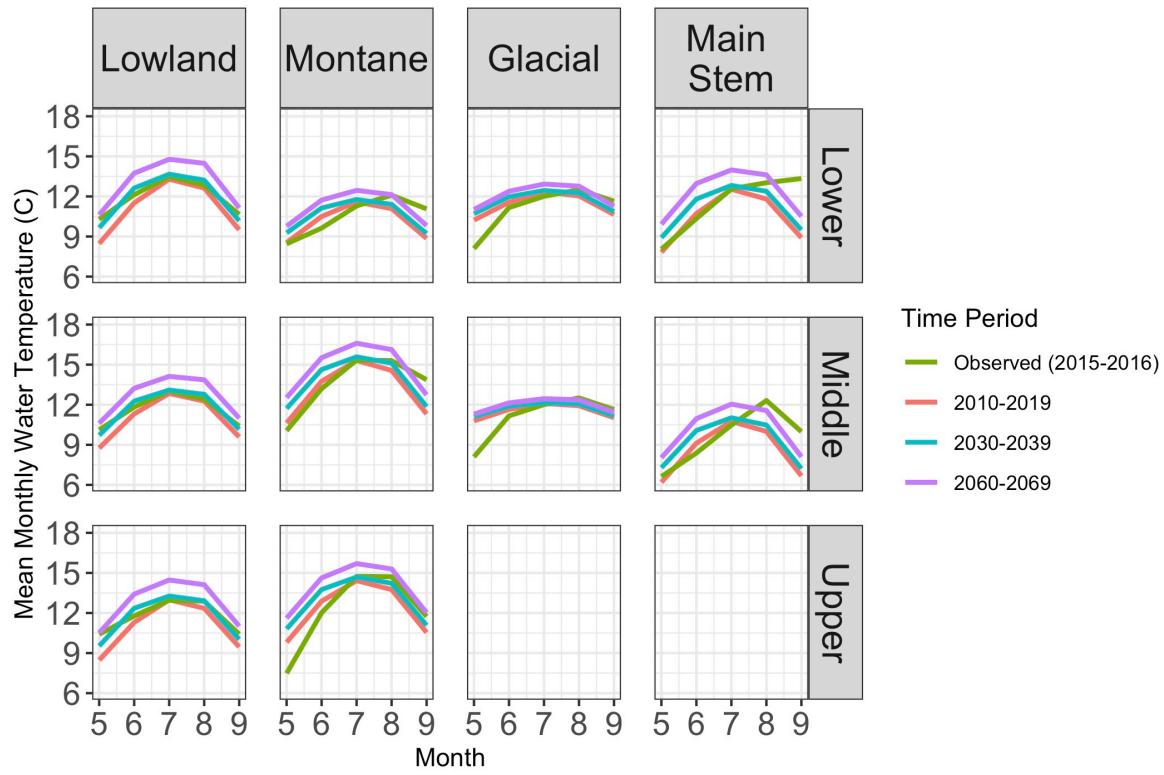
**Figure 1.2.** Schematic of inputs and outputs used in bioenergetics modeling to estimate fish growth under future scenarios. Field data from 2015-2016 were used as inputs in season-length simulations of growth under current conditions, and feeding rate (*p*-value; or proportion of theoretical maximum consumption) estimates were output. Next, future simulations were fit to a range of consumption scenarios scaled relative to these current feeding rates. Water temperature inputs for future scenarios were based on empirical air-water sensitivity relationships and air temperature projections from downscaled climate models. The term “cohort” in the figure refers to a unique combination of site, fish species (Chinook or coho salmon), and fish age (age 0 or 1).



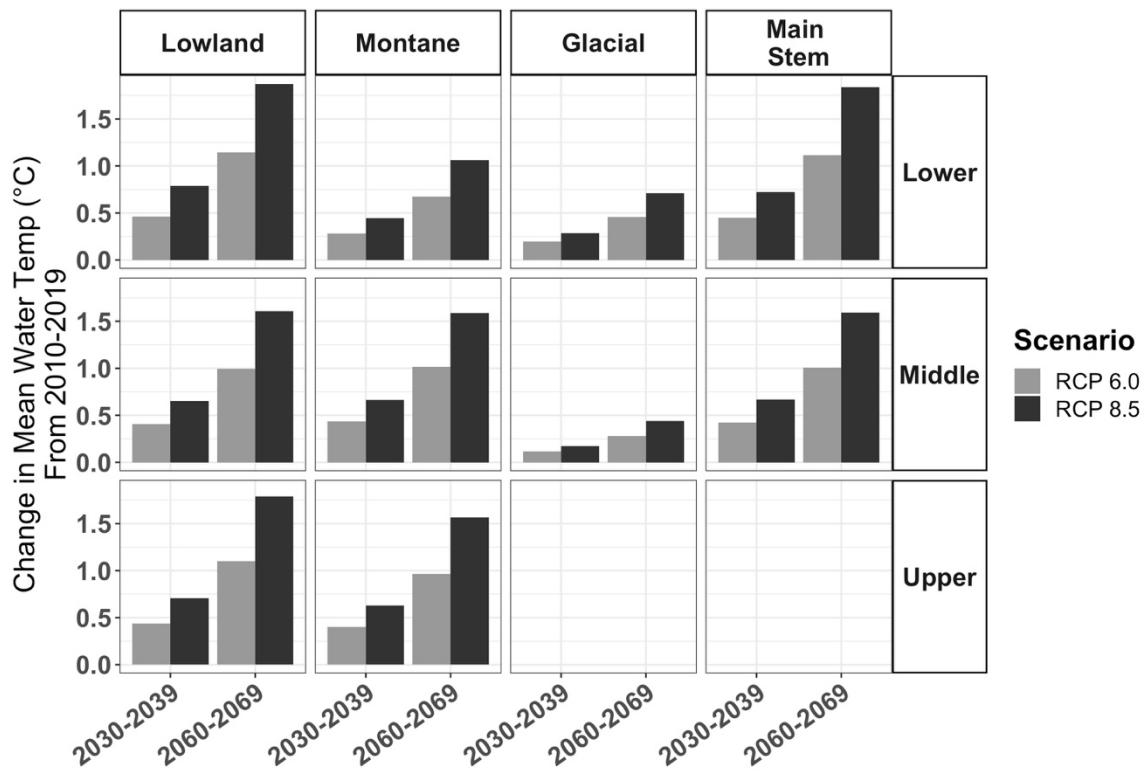
**Figure 1.3.** Observed water temperatures by site and year. Water temperatures shown include those from the subset of time common to all sites and years, June 1<sup>st</sup> – August 20<sup>th</sup>.



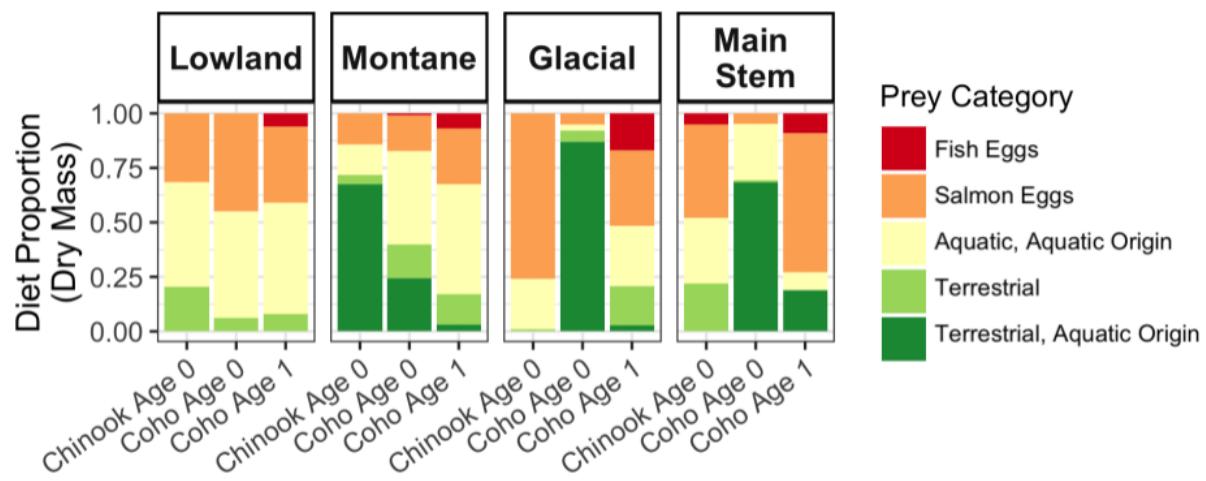
**Figure 1.4.** Linear regressions fit to weekly mean air and water temperature values for each site. Statistically significant relationships ( $p < 0.05$ ) are shown with a blue trend line and gray 95% confidence band. Blank panels indicate data was either not collected at that site or not included in this study. Model output and estimates for individual regressions are available in supplementary table 1.4S.



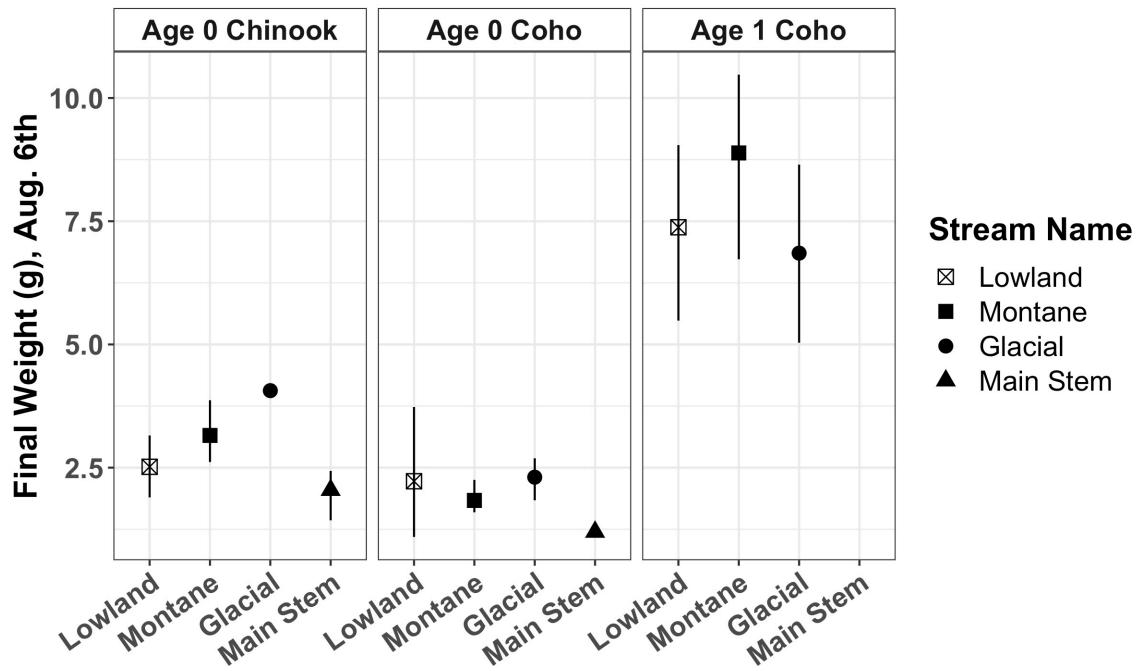
**Figure 1.5.** Observed and modeled water temperature (monthly means, May-September) for each site and time period. Modeled monthly mean temperature values shown are from the RCP 8.5 (rapid increase CO<sub>2</sub> emissions) scenario. Monthly means were not significantly different between the RCP 6.0 (mid-range CO<sub>2</sub> emissions) and RCP 8.5 climate scenarios (Wilcoxon rank-sum,  $p = 0.46$ ,  $W = 12971$ ), and only the RCP 8.5 scenario is shown here.



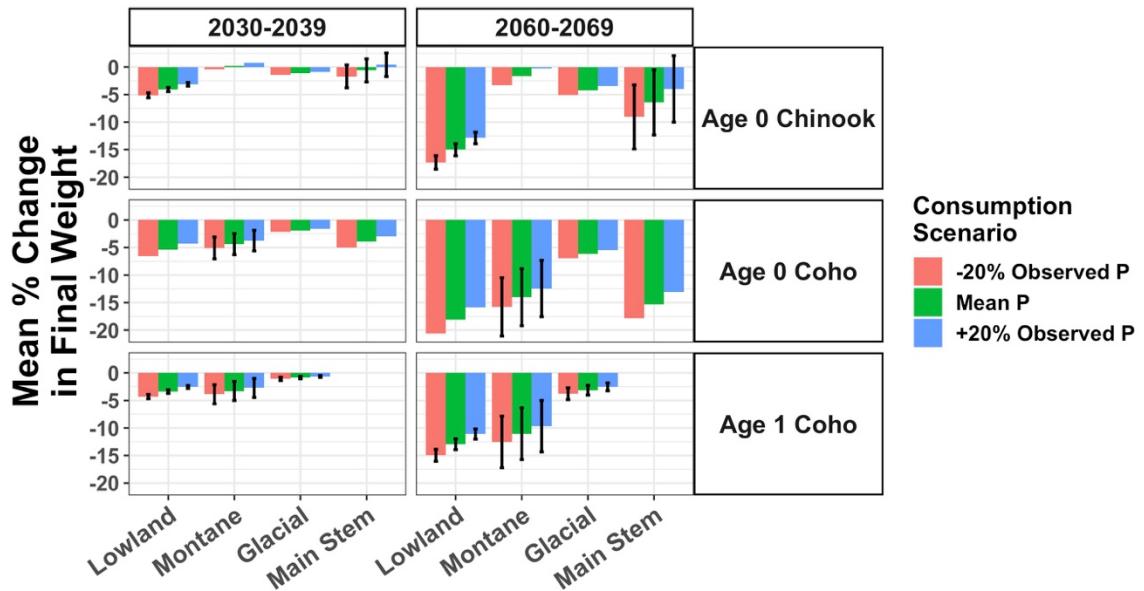
**Figure 1.6.** Change (°C) in mean summer water temperature relative to 2010-2019 simulations for each site, time period, and emission scenario.



**Figure 1.7.** Overall diet proportions segregated by population and drainage. Prey category values are calculated from mean dry mass.



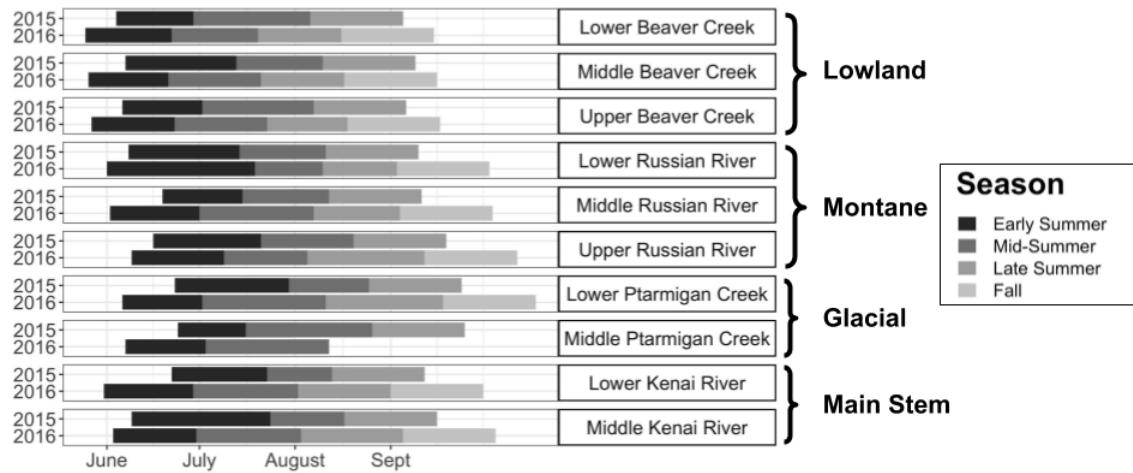
**Figure 1.8.** Final mean size (g) on August 6<sup>th</sup> for fish populations by age and species. Error bars indicate the maximum and minimum values for all years and cohorts within a drainage. Error bars are missing when a small range of minimum and maximum values are obscured behind the point.



**Figure 1.9.** Mean change in simulated juvenile salmon size at end of summer (Sept 4<sup>th</sup>) relative to 2010-2019, based on RCP 8.5 emissions scenarios, ranging from +2.6% to -23.3%. Consumption scenarios indicate mean or  $\pm$  20% of observed feeding rate. Error bars are standard deviation among multiple sites within a watershed. Absence of error bars indicates only one site within a watershed had sufficient population data to perform simulations. See Table 1.4 for full complete results of percent change in simulated size relative to 2010-2019.

## 1.10 Appendices

### Appendix 1.1. Summary of Fish Sampling Periods



**Figure 1.1A.** Temporal extent of sampling periods, defined as the period of days between fish sampling events ( $31 \pm 5$  days, mean  $\pm$  standard error) days). The transition point between seasons denotes a fish sampling event. Three sampling events per site occurred in summer 2015 and four at most sites in summer 2016.

## **Appendix 1.2.** Stream and Air Temperature Monitoring Methods

### *General*

We collected water and air temperature data at a minimum of three sites per tributary along a longitudinal gradient from lower to upper reaches. We recorded data at 15-minute intervals from May to August 2015 and May to September 2016 using water temperature data loggers (HOBO® Temp Pro v2, Onset Corp, Bourne, MA) or Hydrolab sondes (Hydrolab MS-5 Sonde, OTT, Loveland CO) (Figure 1.2B). For the main stem Kenai River, we acquired data from U.S. Geological Survey (USGS) gauge station sites or airport meteorology records from the National Weather Service (NWS). Coordinates and period of deployment for all sensors are summarized in Table 1.2A. Temperature field data were summarized to weekly means.

We checked all loggers for accuracy using methods outlined in Mauger et al. (2015) prior to and post field deployment. We downloaded data at regular intervals (24 - 36 days for the HOBO logger and 10 days for the Hydrolabs), inspected them for anomalies that would suggest malfunction or exposure to air and removed them if so, and replaced loggers as needed. Hydrolab probes were maintained and calibrated in a laboratory on a 10-day scheduled interval according to a manufacturer recommended quality assurance plan on file with the Kenai Watershed Forum (Soldotna, AK).

### *Water Temperature Logger Deployment*

To ensure that water temperature logger sites were not influenced by local thermal anomalies, we selected sites in accordance with standards published in Mauger et al. (2015). At potential monitoring sites we performed channel transects of at least five points to verify that surface (0.1 m depth) and benthic temperatures did not vary greater than 0.25 °C upon logger deployment, retrieval, and opportunistic site visits. At one site where current was too swift to safely perform a channel transect (Middle Ptarmigan Creek) we performed a circular transect in a three meter radius around the logger. We used a Cooper-Atkins AquaTuff Instant Read® Bare Wire thermocouple or YSI® 556 instrument for instantaneous water temperature measurements.

### *Air temperature Logger Deployment*

To understand relationships between air temperature and water temperature, at most sites we installed one logger (HOBO® Water Temp Pro v2) to record air temperature at 15-minute intervals onshore. Loggers were housed in Onset® M-RSA solar radiation shields to block direct solar radiation and maximize airflow. We secured the shields approximately 2 m above the ground to a sturdy tree, out of direct sunlight and in areas of adequate air mixing. We located air temperature monitoring sites well upslope of the stream where possible to minimize air temperature anomalies often associated with riparian zones. We calculated straight-line distance between water temperature logger sites and the nearest air temperature logger site using QGIS 3.4.11 (QGIS Development Team 2019). Distances ( $n = 19$ ) ranged from 3.1 to 14330.0 m, averaging  $2486.4 \pm 4058.6$  (mean  $\pm$  SD).

### *Merging Data from Multiple Sites*

Some water temperature datasets had missing intervals due to exposed or malfunctioning loggers. In order to achieve datasets of greater continuous length, nearby sites were evaluated as potential sources of replacement data. To fill in data gaps we used data from the nearest available logger if datasets were sufficiently similar: we calculated absolute difference values for all concurrent observations between the two sites and considered them sufficiently similar if overall mean absolute difference was  $< 0.2$  °C, which is the same level of precision as the HOBO® TempPro v2 loggers.

Extent of logger deployment and composition of final datasets is summarized in Figure 1.2A.

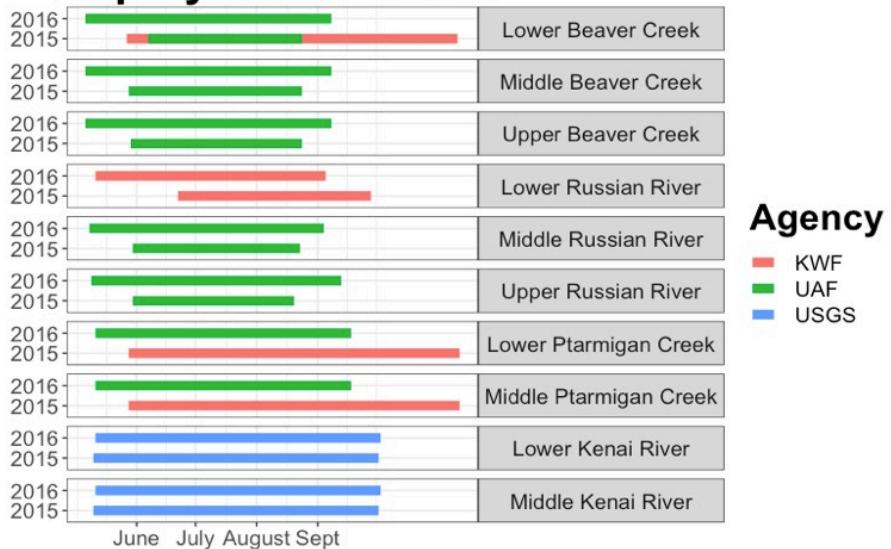
**Table 1.2A.** Locations and coordinates for temperature sensors from 2015 and 2016.

Stream Name	Stream Reach	Data Type	Sensor Model	No. of Sensors	Coordinates		Years Deployed		Agency
					N	W	2015	2016	
Beaver Creek (Lowland)	Middle	Air	HOv2	1	60.560472	-151.125556	X	X	UAF
		Lower Water	HOv2	1	60.560500	-151.125556	X	X	UAF
		Water	HY	2	60.560300	-151.125767	X	X	KWF
		Air	HOv2	1	60.574528	-151.094944	X	X	UAF
	Upper	Water	HOv2	1	60.575639	-151.095750	X	X	UAF
		Air	HOv2	1	60.614917	-151.086528	X	X	UAF
		Water	HOv2	1	60.615083	-151.085972	X	X	UAF
		Air	HOv2	1	60.485139	-149.996500	X	X	UAF
Russian River (Montane)	Middle	Lower Water	HOv2	1	60.485222	-149.996500	X	X	UAF
		Water	HY	2	60.453000	-149.986767	X	X	KWF
		Air	HOv2	1	60.450389	-149.989139	X	X	UAF
		Water	HOv2	1	60.450250	-149.987917	X	X	UAF
	Upper	Air	HOv2	1	60.359556	-149.898222	X	X	UAF
		Water	HOv2	1	60.359500	-149.898722	X	X	UAF
		Air	HOv2	1	60.404167	-149.369333	X	X	UAF
		Lower Water	HOv2	1	60.403722	-149.369611	X	X	UAF
Ptarmigan Creek (Glacial)	Middle	Water	HY	2	60.404833	-149.307611	X	X	KWF
		Air	HOv2	1	60.414000	-149.347194	X	X	UAF
		Water	HOv2	1	60.414056	-149.346639	X	X	UAF
		Air	HOv2	1	60.412417	-149.306167	X	X	UAF
	Upper	Water	HOv2	1	60.412000	-149.307611	X	X	UAF
		Air	-	1	60.579700	-149.239100	X	X	NWS
		Lower Water	GS	1	60.477500	-149.079444	X	X	USGS
		Air	HOv2	1	60.485139	-149.996500	X	X	UAF
Kenai River (Main Stem)	Middle	Water	GS	1	60.497778	-149.807778	X	X	USGS

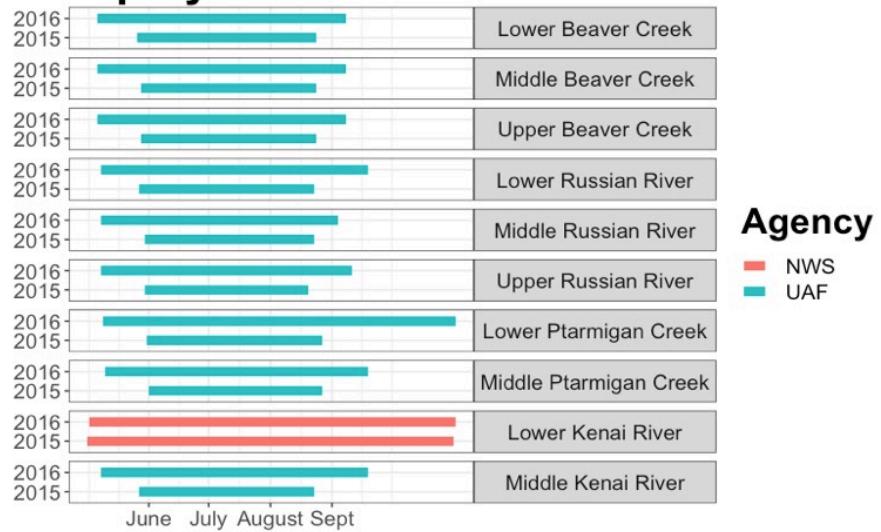
*Sensor Model:* HOv2 = HOBO TempPro v2; HY = Hach Hydrolab, GS = USGS Gauge Station.

*Agency:* UAF = University of Alaska Fairbanks, KWF = Kenai Watershed Forum, USGS = U.S. Geological Survey, NWS = National Weather Service.

## Water Temperature Logger Deployment Periods



## Air Temperature Logger Deployment Periods



**Figure 1.2A.** Deployment lengths for all temperature loggers. Water temperature data (A) was acquired from sites maintained by University of Alaska Fairbanks (UAF), Kenai Watershed Forum (KWF), and United States Geological Service (USGS). Air temperature data (B) was acquired from sites maintained by UAF and the National Weather Service (NWS).

## **Appendix 1.3.** Age Assignment and Assumptions

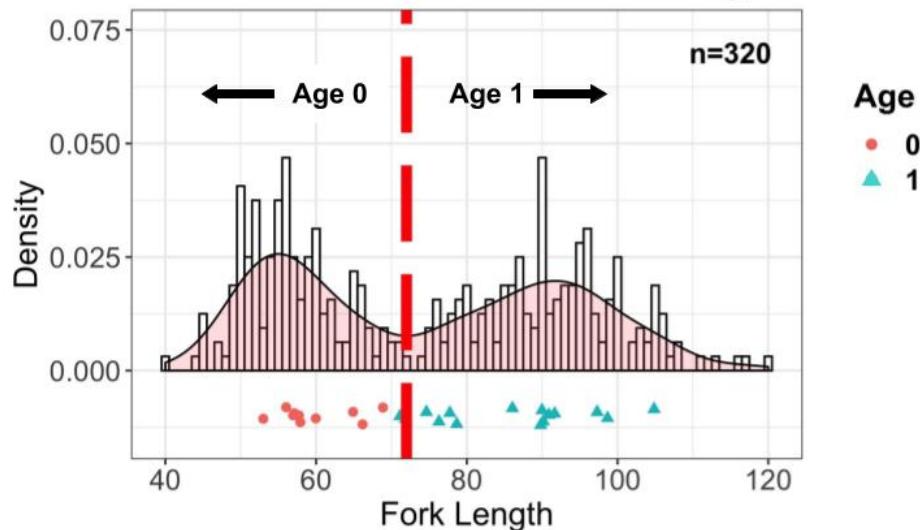
### *Scales Collection and Processing*

We collected five to ten scales from the mesoderm above the lateral line and below the dorsal fin (Minard 1998) of all fish that were sampled for stomach contents, using forceps to gently scrape against the grain. We examined scales selected for analysis under 6.0x magnification with a stereomicroscope and photographed them pressed beneath a glass slipcover. To reduce interpretation bias, two readers estimated the age of juvenile salmon independently without access to information on fish size or time of year of collection. A scale annulus was defined using the criteria of circuli crowding and “cutting over” described by Beamish and McFarlane (1983). Scales to which readers did not assign a consensus age were eliminated from further analysis. Individual ages for salmon from which scales were not collected were assigned through visual inspection of fork length frequency histograms. We generated plots of fork length frequency distribution for fish segregated by year, watershed, species, and sampling event. We used fork length data from fish with manually aged scales to verify the fork length/age threshold values by plotting manually aged scales below the frequency distribution on the horizontal axis.

### *Age Assignment from Scales*

We assigned ages to individuals from which scales were not collected by visual inspection of fork length frequency histograms. We created separate plots for each iteration of species, watershed, year, and season (see Figure 1.3A for example). We plotted aged scales below the x-axis to visualize how the age threshold lined up with their distribution. We manually identified the threshold and assigned ages above and below accordingly.

## Beaver Creek Fall 2016 Coho Fork Lengths



**Figure 1.3A.** Density histogram of fork lengths from Coho salmon captured from Beaver Creek (Lowland watershed) in Fall 2016 ( $n = 320$ ). Threshold between age 0 and age 1 is indicated by the red dashed line. Manually aged scales are plotted below the x-axis.

### *Growth rate estimates from chronological fork length distribution modes*

The progression of fork length modes through time may be used to estimate growth within fish populations (Isely 2007). Use of this method requires several assumptions:

*Assumption 1- Each mode represents a distinct age class.* Fork length data partitioned into distinct modes, each of which we assumed was composed primarily a single age class (ages 0, 1, and 2 for coho salmon, and ages 0 and 1 for Chinook salmon). In order to verify the age composition of each mode we aged scales from individuals within each mode as available and verified the age assignment.

*Assumption 2- Growth rates across age classes is similar through time.* Juvenile growth rates for each year (partitioned by age, year, species, and site) was drawn from

a sample size sufficiently large so as to minimize the likelihood of uneven growth rates among age classes.

*Assumption 3- The sample is drawn at random with respect to size.* We used minnow traps as the exclusive gear type used in this study, and mesh size and trap entrance diameter were consistent across all sampling events. A fixed trap entrance diameter may bias against capture of larger fish, while mesh size may bias against retention of smaller fish. For the particular species and age classes of interest in this study it is anticipated that these biases were minimal.

#### Appendix 1.4. Linear mixed model assessment of temporal/spatial scales of growth

We used a linear mixed modeling approach to assess how spatial and temporal predictors relate to growth rate metrics. We fit three models, each with a different response, to sets of predictor variables. We used year, species, and age as fixed variables and site as a random variable (Table 1.D1).

**Table 1.4A.1** Variables and levels for linear mixed model to determine spatial and temporal scales of growth simulations.

Species (Fixed)	Age (Fixed)	Year (Fixed)	Site (Random)
Chinook	0	2015	Lower Beaver Creek
Coho	1	2016	Lower Russian River
			Lower Ptarmigan Creek
			Lower Kenai River
			Middle Beaver Creek
			Middle Russian River
			Middle Ptarmigan Creek
			Middle Kenai River
			Upper Beaver Creek
			Upper Russian River

The three models considered are as follows:

- A. Individual Weight ~ (1 | Site) + Julian Day + Species + Age + Year
  - o (n = 4275 total fish weights)
- B. Mass-Specific Growth Rate ~ (1 | Site) + Season + Species + Age + Year
  - o (n = 55 seasonal mass-specific growth rate values ( $\text{g}\cdot\text{g}^{-1}\cdot\text{d}^{-1}$ ). A season is defined as the interval of days between two sampling events at a site, approximately monthly intervals. Specific growth rate values were calculated using the equation

$$(1) \quad G = \frac{\ln(W_{t_2}) - \ln(W_{t_1})}{t_2 - t_1}$$

where  $W_{t2}$  is the mean weight of a fish population from a sampling event on Julian day  $t_2$ , and  $W_{t1}$  is the mean weight of fish from the site's prior sample event.

- C. Final Weight (Weight on Aug. 6<sup>th</sup>)  $\sim (1 | \text{Site}) + \text{Species} + \text{Age} + \text{Year}$ 
  - o ( $n = 45$  available values for fish weight on the Julian day of earliest final site visit across all sites and years).

For all approaches, we used fish weights calculated from age-segregated back-transformations of length and weight data as described in Ogle (2016). We used back-transformed weight rather than raw values as a response variable because stomach content mass can introduce error especially for small fish like those of our study population. A log transformation was applied to the back-transformed weight values to improve linearity of the relationship with time. Residual plots were visually inspected to verify random distribution. For the third approach, we used interpolated weight values acquired from a linear trend between mean weight values of last two sequential site visits of each field season. August 6<sup>th</sup> (Julian Day 218) was the earliest day for a final site visit among both years and all sites, and we calculated interpolated weight values for this date.

Model results from the three relationships are arranged in Table 1.D2. After controlling for site-level variation, all predictors were significant covariates ( $p < 0.05$ ) in Approach A (individual fish weight vs. Julian day). Only season was a significant covariate in Approach B (mean daily growth rate vs. season). Year and age were significant covariates in Approach C (growth potential; or size at end of summer). We retained all variables as factors by which to segregate fish size and growth data as inputs in bioenergetics models that used observed field data. Approach C offered the best correlation between predictors and response ( $R^2_{\text{adj}} = 0.86$ ) and was selected as the response for which to compare in future scenarios.

**Table 1.4A.2** Three linear mixed model results used to identify effect sizes of spatial and temporal predictor variables on growth and size responses.

	Mass <sup>a</sup>	Seasonal Growth Rate <sup>b</sup>	Final Size <sup>c</sup>
Julian day	0.0071 *** (0.0002)		
Year (2016)	0.2085 *** (0.0126)	0.0015 (0.0015)	0.8599 * (0.338)
Species (Coho)	-0.3551 *** (0.0193)	0.0003 (0.0019)	-0.6249 (0.4136)
Age (Age 1)	1.3027 (0.0190)	-0.0017 (-0.0017)	5.8631 *** (0.3772)
Season		-0.0037 *** (0.0010)	
N	4226	55	45
N (Site)	10	10	10
AIC	3517.8110	-362.3963	146.0357
BIC	3562.2541	-348.3450	156.8757
R <sup>2</sup> (fixed)	0.6356	0.1984	0.8604
R <sup>2</sup> (total)	0.7097	0.2076	0.8645

\*\*\* p < 0.001; \*\* p < 0.01; \* p < 0.05

a.) Individual fish mass; b.) Slope of the line between mean fish sizes between two site visits; c.) Fish mass on August 6<sup>th</sup>.

## **1.11 Supplementary Information**

**Table 1.1S.** Coordinates of fish sampling sites.

River	Reach	Latitude	Longitude
Beaver Creek (Lowland)	Lower	60.560500	-151.125556
	Middle	60.570139	-151.103444
	Upper	60.615139	-151.086194
Russian River (Montane)	Lower	60.484611	-149.993639
	Middle	60.450028	-149.987472
	Upper	60.368250	-149.934889
Ptarmigan Creek (Glacial)	Lower	60.403750	-149.369806
	Middle	60.409472	-149.356833
Kenai River (Main Stem)	Lower	60.483389	-151.125972
	Middle	60.485750	-149.996250

**Table 1.2S.** Summaries of juvenile Chinook and coho salmon fork length (FL) and weight (g) from the Kenai River, Alaska. Values are summarized as means (standard deviations). Starred (\*) fish count data indicates that fewer than three individuals of that population were captured in a sampling event and data were not used to calculate mean weight inputs for bioenergetics simulations (page 1 of 5).

Watershed	Reach	Species	Age	Year	Sample Event	Sample Event Date	Fork Length (mm)	Weight (g)	Back-calculated Weight (g)	Fish Count	Diets Collected
Lowland (Beaver Creek)	Lower	Chinook	0	2015	2	6/29/2015	54.0 (NA)	2.0 (NA)	1.8 (NA)	1*	1
				2016	2	6/21/2016	50.1 (4.0)	1.5 (0.4)	1.5 (0.4)	73	12
				2016	3	7/19/2016	54.8 (6.8)	1.9 (0.8)	1.9 (0.8)	59	9
				2016	4	8/15/2016	54.6 (6.1)	2.0 (0.8)	1.9 (0.6)	16	8
	Coho	0	2015	2	6/29/2015	41.3 (1.2)	0.9 (0.1)	0.8 (0.1)	6	0	
				2015	3	8/6/2015	46.1 (4.7)	1.3 (0.5)	1.1 (0.4)	19	1
				2016	2	6/21/2016	53.8 (8.1)	1.9 (0.6)	1.9 (0.7)	9	1
				2016	3	7/19/2016	51.9 (7.8)	1.7 (0.9)	1.7 (0.8)	26	4
				2016	4	8/15/2016	56.3 (7.2)	2.1 (0.9)	2.1 (0.9)	119	8
		1	2015	1	6/4/2015	69.0 (7.7)	3.4 (1.4)	3.9 (1.4)	46	14	
				2015	2	6/29/2015	71.2 (7.7)	4.4 (1.5)	4.2 (1.4)	68	16
				2015	3	8/6/2015	80.3 (13.0)	6.6 (2.9)	6.3 (3.0)	38	15
				2016	1	5/24/2016	69.4 (9.5)	3.6 (1.9)	4.0 (2.0)	48	15
				2016	2	6/21/2016	78.4 (11.1)	5.8 (2.7)	5.8 (2.7)	93	8
				2016	3	7/19/2016	89.2 (11.3)	7.6 (3.2)	8.4 (3.4)	18	7
				2016	4	8/15/2016	92.4 (5.6)	9.2 (1.7)	9.0 (1.8)	17	2
Middle	Chinook	0	2016	2	6/20/2016	52.3 (4.4)	1.6 (0.4)	1.6 (0.4)	12	7	
				2016	3	7/20/2016	59.3 (6.0)	2.5 (0.9)	2.4 (0.8)	20	11
				2016	4	8/16/2016	61.8 (4.7)	2.7 (0.6)	2.7 (0.6)	13	11
	Coho	0	2015	3	8/10/2015	45.0 (NA)	1.2 (NA)	1.0 (NA)	1*	0	
				2016	3	7/20/2016	64.3 (7.5)	3.0 (0.9)	3.1 (1.0)	15	3
				2016	4	8/16/2016	62.5 (9.2)	2.9 (1.3)	2.9 (1.3)	35	5
		1	2015	1	6/7/2015	76.1 (9.2)	5.5 (2.1)	5.2 (2.0)	19	8	
				2015	2	7/13/2015	77.7 (11.9)	6.1 (2.6)	5.7 (2.4)	33	16
				2015	3	8/10/2015	80.0 (11.1)	6.2 (2.6)	6.1 (2.5)	69	16
				2016	1	5/25/2016	74.6 (9.3)	4.8 (1.7)	4.9 (2.2)	50	14
				2016	2	6/20/2016	79.6 (9.3)	6.0 (2.2)	6.0 (2.2)	108	10

**Table 1.2S.** Continued, (page 2 of 5)

Watershed	Reach	Species	Age	Year	Sample Event	Sample Event Date	Fork Length (mm)	Weight (g)	Back-calculated Weight (g)	Fish Count	Diets Collected
Lowland (Beaver Creek)	Upper	Coho	1	2016	3	7/20/2016	85.1 (6.2)	7.3 (1.7)	7.1 (1.5)	70	6
				2016	4	8/16/2016	93.3 (8.7)	9.1 (3.1)	9.5 (2.9)	43	4
	Chinook	0	2016	3	7/22/2016	64.5 (2.5)	3.1 (0.3)	3.0 (0.3)	4	4	
			2016	4	8/17/2016	66.8 (6.8)	3.3 (0.9)	3.4 (1.1)	5	5	
	Coho	0	2016	3	7/22/2016	68.0 (NA)	4.0 (NA)	3.5 (NA)	1*	1	
			2016	4	8/17/2016	71.3 (9.3)	4.2 (1.5)	4.2 (1.4)	26	4	
		1	2015	1	6/6/2015	87.1 (7.0)	8.0 (1.9)	7.6 (1.8)	20	5	
			2015	2	7/2/2015	80.7 (8.2)	6.4 (2.1)	6.1 (1.9)	38	15	
			2015	3	8/7/2015	83.4 (9.0)	6.9 (2.3)	6.8 (2.2)	68	14	
			2016	1	5/26/2016	82.4 (10.1)	6.6 (2.8)	6.6 (2.7)	14	9	
			2016	2	6/22/2016	87.8 (7.8)	8.2 (2.2)	7.9 (2.0)	91	10	
			2016	3	7/22/2016	90.7 (8.2)	9.0 (2.7)	8.7 (2.4)	102	9	
			2016	4	8/17/2016	94.9 (8.0)	9.8 (2.5)	9.9 (2.5)	79	6	
Montane (Russian River)	Lower	Chinook	0	2015	1	6/8/2015	51.4 (5.7)	1.7 (0.6)	1.6 (0.6)	23	7
				2015	2	7/14/2015	54.5 (6.2)	2.0 (0.7)	1.9 (0.6)	4	3
				2015	3	8/11/2015	71.0 (NA)	4.3 (NA)	4.0 (NA)	1*	0
				2016	1	5/31/2016	48.6 (4.4)	1.3 (0.4)	1.3 (0.4)	30	5
				2016	2	7/18/2016	65.6 (5.5)	3.2 (0.9)	3.2 (0.8)	19	8
				2016	3	8/9/2016	63.5 (3.5)	2.9 (0.1)	2.9 (0.5)	2*	2
				2016	4	9/2/2016	71.8 (8.9)	4.2 (1.6)	4.3 (1.5)	5	5
	Coho	0	2015	1	6/8/2015	40.5 (2.1)	0.8 (0.1)	0.8 (0.1)	2*	0	
			2015	2	7/14/2015	50.1 (4.8)	1.4 (0.4)	1.5 (0.4)	58	14	
			2015	3	8/11/2015	55.9 (8.0)	2.1 (0.9)	2.1 (0.9)	58	17	
			2016	1	5/31/2016	40.5 (0.7)	0.9 (0.1)	0.8 (0.0)	2*	0	
			2016	2	7/18/2016	53.5 (4.9)	1.7 (0.5)	1.8 (0.5)	86	8	
			2016	3	8/9/2016	56.5 (4.8)	2.0 (0.5)	2.1 (0.5)	71	10	
			2016	4	9/2/2016	53.3 (7.1)	1.7 (0.9)	1.8 (0.8)	44	10	

**Table 1.2S.** Continued, (page 3 of 5)

Watershed	Reach	Species	Age	Year	Sample Event	Sample Event Date	Fork Length (mm)	Weight (g)	Back-calculated Weight (g)	Fish Count	Diets Collected
Montane (Russian River)	Lower	Coho	1	2015	1	6/8/2015	66.8 (6.8)	3.5 (1.0)	3.5 (1.1)	10	6
				2015	2	7/14/2015	84.0 (NA)	6.0 (NA)	6.7 (NA)	1*	1
				2016	1	5/31/2016	68.1 (5.7)	3.8 (0.9)	3.7 (0.9)	33	8
				2016	2	7/18/2016	79.5 (6.7)	5.8 (1.5)	5.8 (1.5)	6	4
	Chinook		0	2016	1	6/1/2016	48.0 (0.0)	1.4 (0.3)	1.3 (0.0)	2*	0
				2016	2	6/30/2016	68.0 (NA)	3.6 (NA)	3.5 (NA)	1*	1
				2016	3	8/6/2016	68.5 (6.4)	3.8 (1.0)	3.6 (1.0)	2*	2
				2016	4	9/3/2016	62.0 (8.2)	2.8 (0.6)	2.8 (1.0)	3	3
	Coho		0	2015	1	6/19/2015	46.1 (3.1)	1.4 (0.3)	1.1 (0.2)	29	1
				2015	2	7/15/2015	49.2 (7.5)	1.4 (0.7)	1.4 (0.8)	50	9
				2015	3	8/12/2015	54.9 (7.0)	1.9 (0.7)	2.0 (0.7)	56	8
				2016	1	6/1/2016	50.0 (NA)	1.6 (NA)	1.4 (NA)	1*	0
				2016	2	6/30/2016	48.9 (5.7)	1.4 (0.6)	1.4 (0.6)	43	4
				2016	3	8/6/2016	62.7 (7.0)	2.9 (1.0)	2.9 (0.9)	65	12
				2016	4	9/3/2016	60.8 (7.3)	2.5 (0.8)	2.6 (0.9)	25	10
Upper	Chinook		1	2015	1	6/19/2015	72.8 (15.9)	5.8 (3.5)	5.0 (3.1)	11	11
				2015	2	7/15/2015	90.3 (6.7)	7.8 (1.3)	8.5 (1.8)	3	3
				2015	3	8/12/2015	97.3 (2.5)	10.3 (0.9)	10.5 (0.8)	8	8
				2016	1	6/1/2016	73.5 (7.8)	4.5 (1.6)	4.7 (1.6)	45	11
				2016	2	6/30/2016	83.4 (9.3)	6.9 (2.3)	6.8 (2.4)	16	6
				2016	3	8/6/2016	93.4 (6.8)	8.9 (1.9)	9.4 (2.1)	10	2
	Coho		0	2015	1	6/16/2015	54.0 (2.8)	1.8 (0.3)	1.8 (0.3)	2*	2
				2015	2	7/21/2015	62.0 (7.1)	2.7 (1.0)	2.7 (0.9)	2*	1
				2016	1	6/8/2016	57.0 (2.8)	2.3 (0.6)	2.1 (0.3)	5	4
				2016	3	8/4/2016	70.0 (NA)	3.7 (NA)	3.8 (NA)	1*	1
	Coho		0	2015	1	6/16/2015	44.2 (2.3)	1.5 (0.8)	1.0 (0.2)	6	0
				2015	2	7/21/2015	51.4 (6.7)	1.6 (0.7)	1.6 (0.7)	36	12

**Table 1.2S.** Continued, (page 4 of 5)

Watershed	Reach	Species	Age	Year	Sample Event	Sample Event Date	Fork Length (mm)	Weight (g)	Back-calculated Weight (g)	Fish Count	Diets Collected
Glacial (Ptarmigan Creek)	Lower Middle	Coho	1	2016	3	8/10/2016	87.2 (9.0)	7.6 (2.6)	7.7 (2.4)	59	7
		Coho	0	2015	1	6/24/2015	48.5 (0.7)	1.6 (0.5)	1.3 (0.1)	2*	0
				2015	2	7/16/2015	55.0 (NA)	2.1 (NA)	1.9 (NA)	1*	1
				2015	3	8/26/2015	65.6 (1.9)	3.2 (0.3)	3.2 (0.3)	7	3
				2016	3	8/11/2016	65.0 (NA)	3.1 (NA)	3.1 (NA)	1*	0
			1	2015	1	6/24/2015	86.6 (9.9)	7.7 (2.7)	7.6 (2.6)	23	16
				2015	2	7/16/2015	78.1 (7.9)	5.5 (1.8)	5.6 (1.7)	19	19
				2015	3	8/26/2015	85.5 (10.4)	7.0 (2.5)	7.4 (2.8)	45	13
				2016	1	6/6/2016	92.0 (NA)	8.6 (NA)	8.8 (NA)	1*	1
				2016	2	7/2/2016	87.8 (10.8)	7.4 (2.5)	8.0 (3.1)	11	10
				2016	3	8/11/2016	92.6 (10.4)	9.0 (3.1)	9.4 (3.2)	25	10
				2016	1	5/26/2016	109.0 (NA)	11.4 (NA)	14.7 (NA)	1*	0
Main Stem (Kenai River)	Lower	Chinook	0	2015	1	6/22/2015	49.2 (4.1)	1.3 (0.4)	1.4 (0.4)	86	13
				2015	2	7/23/2015	51.4 (8.7)	1.8 (1.0)	1.7 (0.9)	17	9
				2015	3	8/13/2015	42.0 (NA)	0.9 (NA)	0.8 (NA)	1*	0
				2016	1	5/30/2016	47.0 (2.0)	1.4 (0.1)	1.2 (0.1)	3	0
				2016	2	6/28/2016	57.1 (5.7)	2.3 (0.7)	2.2 (0.6)	86	11
				2016	3	8/1/2016	57.3 (5.7)	2.2 (0.8)	2.2 (0.7)	115	10
				2016	4	8/31/2016	65.6 (8.4)	3.4 (1.3)	3.3 (1.2)	120	10
		Coho	0	2015	2	7/23/2015	46.5 (4.2)	1.2 (0.4)	1.2 (0.3)	27	4
				2015	3	8/13/2015	48.8 (4.7)	1.4 (0.5)	1.3 (0.4)	67	10
				2016	3	8/1/2016	49.4 (8.1)	1.5 (0.9)	1.5 (0.8)	8	2
				2016	4	8/31/2016	49.8 (6.5)	1.4 (0.6)	1.5 (0.6)	34	9
			1	2015	1	6/22/2015	55.0 (NA)	1.9 (NA)	1.9 (NA)	1*	1
				2015	2	7/23/2015	85.0 (NA)	6.9 (NA)	7.0 (NA)	1*	1
				2016	1	5/30/2016	72.0 (NA)	5.3 (NA)	4.2 (NA)	1*	1
				2016	3	8/1/2016	85.5 (0.7)	7.1 (1.1)	7.1 (0.2)	2*	2

**Table 1.2S.** Continued, (page 5 of 5)

Watershed	Reach	Species	Age	Year	Sample Event	Sample Event Date	Fork Length (mm)	Weight (g)	Back-calculated Weight (g)	Fish Count	Diets Collected
Main Stem (Kenai River)	Lower	Coho	1	2016	4	8/31/2016	96.0 (NA)	9.7 (NA)	10.0 (NA)	1*	1
	Middle	Chinook	0	2015	1	6/9/2015	53.0 (1.4)	1.9 (0.0)	1.7 (0.1)	2*	0
			2015	2	7/24/2015	56.4 (6.4)	2.1 (0.8)	2.1 (0.7)	39	16	
			2015	3	8/17/2015	62.0 (6.2)	2.8 (0.7)	2.7 (0.8)	5	5	
			2016	1	6/2/2016	45.3 (3.0)	1.0 (0.2)	1.1 (0.2)	52	4	
			2016	2	6/29/2016	51.6 (4.1)	1.5 (0.4)	1.6 (0.4)	168	10	
			2016	3	8/2/2016	58.9 (8.3)	2.5 (1.0)	2.4 (1.0)	108	9	
			2016	4	9/4/2016	59.2 (7.4)	2.4 (0.9)	2.4 (0.9)	38	10	
	Coho	0	2015	2	7/24/2015	45.0 (1.0)	1.0 (0.1)	1.0 (0.1)	3	0	
			2015	3	8/17/2015	47.7 (4.1)	1.3 (0.4)	1.3 (0.4)	63	6	
			2016	3	8/2/2016	46.1 (8.0)	1.3 (0.7)	1.2 (0.7)	11	2	
			2016	4	9/4/2016	48.7 (3.9)	1.3 (0.4)	1.3 (0.3)	63	9	
	1	2015	2	7/24/2015	72.0 (NA)	4.5 (NA)	4.2 (NA)	1*	1		
		2015	3	8/17/2015	104.0 (NA)	11.6 (NA)	12.8 (NA)	1*	1		
		2016	1	6/2/2016	68.5 (9.2)	3.8 (1.1)	3.7 (1.5)	2*	1		
		2016	3	8/2/2016	84.0 (NA)	6.0 (NA)	6.7 (NA)	1*	1		

**Table 1.3S.** Input weight values for 2015-2016 bioenergetics simulations and resultant P-values (proportion of maximum consumption) used for modeling future scenarios (page 1 of 2).

Watershed	Reach	Age	Species	Year	Season	Start Day	End Day	Start Weight (g)	End Weight (g)	P-value	
Beaver Creek (Lowland)	Lower	0	Chinook	2016	Mid-Summer	174	201	1.47	1.94	0.30	
				2016	Late Summer	202	228	1.89	1.93	0.19	
		1	Coho	2015	Mid-Summer	181	218	0.82	1.14	0.26	
				2016	Mid-Summer	174	201	1.68	1.85	0.17	
			2016	2016	Late Summer	202	228	1.69	2.11	0.29	
				2015	Mid-Summer	181	218	4.30	6.32	0.32	
				2016	Early Summer	146	173	4.08	5.80	0.34	
			2016	2016	Mid-Summer	174	201	5.88	8.42	0.39	
				2016	Late Summer	202	228	8.40	9.04	0.25	
Middle	0	Chinook	2016	Mid-Summer	173	202	1.67	2.41	0.32		
			2016	Late Summer	203	229	2.41	2.68	0.24		
		1	Coho	2015	Early Summer	159	194	5.23	5.67	0.22	
				2015	Mid-Summer	195	222	5.69	6.15	0.24	
			2016	2016	Early Summer	147	172	4.97	5.96	0.27	
				2016	Mid-Summer	173	202	6.01	7.11	0.28	
				2016	Late Summer	203	229	7.16	9.47	0.35	
	Upper	0	Chinook	2016	Late Summer	205	230	3.02	3.41	0.26	
				2016	Early Summer	148	174	6.68	7.87	0.28	
		1	Coho	2016	Mid-Summer	175	204	7.90	8.67	0.26	
				2016	Late Summer	205	230	8.71	9.91	0.28	
Russian River (Montane)	Lower	0	Chinook	2016	Early Summer	153	200	1.36	3.22	0.21	
				2016	Mid-Summer	201	222	1.78	2.07	0.21	
		1	2016	2016	Late Summer	223	246	1.80	2.06	0.10	
	Middle			2016	Early Summer	153	200	3.70	5.80	0.33	
	0		2015	Early Summer	171	196	1.14	1.44	0.25		
			2015	Mid-Summer	197	224	1.46	1.95	0.29		

**Table 1.3S.** Continued (page 2 of 2)

Watershed	Reach	Age	Species	Year	Season	Start	End	Start	End	P-
						Day	Day	Weight (g)	Weight (g)	value
Russian River (Montane)	Middle	0	Coho	2016	Mid-Summer	183	219	1.41	2.85	0.37
					Late Summer	220	247	2.63	2.84	0.16
		1	2015	Early Summer	171	196	5.08	8.46	0.55	
				2015	Mid-Summer	197	224	8.55	10.46	0.43
			2016	Early Summer	154	182	4.72	6.81	0.40	
				2016	Mid-Summer	183	219	6.90	9.38	0.41
	Upper	0	Coho	2015	Early Summer	168	202	1.00	1.61	0.28
					Mid-Summer	203	232	1.63	1.89	0.26
		1	2016	Mid-Summer	191	217	1.60	2.15	0.28	
				2016	Late Summer	218	255	2.16	2.53	0.20
			2015	Early Summer	168	202	3.77	7.43	0.51	
				2016	Mid-Summer	191	217	8.29	9.68	0.19
Ptarmigan Creek (Glacial)	Lower	0	Chinook	2016	Mid-Summer	184	223	3.23	4.53	0.37
					Late Summer	224	261	3.06	3.12	0.09
		1	Coho	2015	Early Summer	175	211	4.23	5.04	0.25
					Mid-Summer	212	237	5.09	6.19	0.32
			2016	Early Summer	158	183	3.98	5.53	0.36	
				2016	Mid-Summer	184	223	5.59	7.75	0.32
	Middle	1	Coho	2015	Mid-Summer	198	223	5.64	7.42	0.36
					Mid-Summer	185	224	8.05	9.36	0.27
Kenai River (Main Stem)	Lower	0	Chinook	2015	Early Summer	174	204	1.38	1.66	0.27
					Early Summer	152	180	1.21	2.15	0.45
		2016	Coho	Mid-Summer	181	214	2.15	2.20	0.24	
				Late Summer	215	244	2.21	3.31	0.40	
			Coho	Mid-Summer	205	225	1.18	1.35	0.13	
				Late Summer	215	244	1.45	1.46	0.09	
	Middle	0	Chinook	2015	Mid-Summer	206	229	2.12	2.73	0.36
					Late Summer	216	248	2.39	2.44	0.23
		2016	Coho	Mid-Summer	206	229	1.05	1.26	0.12	
				Late Summer	216	248	1.21	1.33	0.10	

**Table 1.4S.** Model output for linear regressions used to generate air-water sensitivity values for each site. Temperature values were summed to weekly means.

Watershed	Reach	Term	Estimate	Std. Error (Term)	p-value (Term)	F-statistic (Term)	r <sup>2</sup> (Fit)	p-value (Fit)
Lowland (Beaver Creek)	Lower	(Intercept)	2.75	1.41	0.07	1.95	0.70	0.00
		Air	0.74	0.10	0.00	7.20		
	Middle	(Intercept)	3.77	1.39	0.01	2.71	0.63	0.00
		Air	0.64	0.10	0.00	6.27		
Montane (Russian River)	Upper	(Intercept)	2.97	1.75	0.11	1.70	0.61	0.00
		Air	0.71	0.13	0.00	5.44		
	Lower	(Intercept)	4.81	2.71	0.09	1.78	0.19	0.03
		Air	0.45	0.19	0.03	2.35		
Glacial (Ptarmigan Creek)	Middle	(Intercept)	5.54	1.98	0.01	2.81	0.48	0.00
		Air	0.68	0.15	0.00	4.64		
	Upper	(Intercept)	5.05	2.65	0.07	1.90	0.32	0.00
		Air	0.67	0.20	0.00	3.35		
Main Stem (Kenai River)	Lower	(Intercept)	7.86	1.76	0.00	4.46	0.17	0.03
		Air	0.32	0.14	0.03	2.30		
	Middle	(Intercept)	9.37	1.83	0.00	5.11	0.04	0.18
		Air	0.20	0.14	0.18	1.38		

## **Section 1.1S. The Wisconsin Bioenergetics Model**

### *The Model*

The Wisconsin Model includes mathematical algorithms designed to mimic physiological processes in fish. The Wisconsin Model assumes that inputs, gains and losses of energy can be balanced. In the balanced energy equation, consumption is the energy input, growth is the net energy gain, and all other uses are losses. The balanced energy equation is represented by the following formula (Hanson 1997):

$$C = B + R + A + S + F + U$$

where,

C = rate of energy consumption

B = somatic tissue growth

R = standard metabolic rate

A = active metabolism

S = metabolic rate from specific dynamic action (heat increment)

F = waste losses due to egestion (feces)

U = waste losses due to excretion (urine)

Rearranged to calculate growth:

$$B = C - (R+A+S) - (F+U)$$

The Wisconsin model accounts for the energy intake by fish, which are simulated by species-specific algorithms that balance the equation as the fish grows over time (Brandt and Hartman 1993). The model calculates each component of the energy budget based on species-specific growth coefficients and parameters that have been derived by previous laboratory experimentation and physiological research. The model also accounts for the non-linear effects on these parameters and coefficients due to variables such as temperature and food intake (Hanson 1997). Among many benefits of the Wisconsin model, only a few inputs are required to run this model after

physiological responses have been identified. The Wisconsin Model simulates the average growth of a fish within a population and population data are then projected from that average individual.

#### *Development and Parameter Selection*

Model development is accomplished by first selecting equations that mathematically represent energetic processes occurring in juvenile Chinook and coho salmon. Rates of energy consumption, respiration, egestion and excretion can all be expressed as non-linear functions of fish weight and water temperature. Temperature is an important factor in all energetic processes and all the equations used to represent the energetic components of the Wisconsin Model are regulated by temperature. When algorithms representing the individual components of consumption, respiration, excretion, egestion and energy density are combined, they define the flow of energy through a fish. Most parameters used in the bioenergetics model are species-specific physiological parameters that are dependent on fish size and water temperature

For input parameters not measured directly in the field, data pertaining to juvenile Chinook and coho salmon energetics were obtained from values included with Fishbioenergetics 4.0 software (Deslauriers et al. 2017). Indigestibility values of 17% and 3% were assigned, respectively, to invertebrate and fish diet items (Beauchamp 2007).



## **Chapter 2. Can water temperatures at downstream sites reflect upstream thermal regimes in Gulf of Alaska streams?<sup>2</sup>**

### **2.1 Abstract**

Water temperature is of central importance in freshwater ecology, thus characterizing stream temperature heterogeneity is critical for assessing ongoing climate change-driven shifts in stream thermal regimes. In-situ water temperature data in remote, challenging-to-access salmon-bearing streams is often monitored at a single site in the lower reach and used to approximate upstream thermal conditions. Monitoring efforts that aim to deploy an efficient sensor array to characterize thermal heterogeneity throughout a watershed are tasked with choosing appropriate quantities and locations of logger sites. We examined two summer seasons of continuous water temperatures from sensors ( $n = 12$ ) throughout three tributaries across a lowland-to-glacial geomorphic spectrum of the Kenai River in south-central Alaska, a watershed with physiography encompassing that of the broader Gulf of Alaska region. We found that for daily mean values and a suite of 39 seasonal thermal regime descriptors, lower-reach sites were generally correlated with upstream sites in our lowland and glacial watersheds, but relationships were less consistent in the montane (intermediate physiography between lowland and glacial) watershed. Additionally, we compared logger data to instantaneous water temperature values measured at nearby minnow traps ( $n = 426$ ) where juvenile Chinook and coho salmon were captured. Most observations (69%) at traps occupied by salmon exhibited less than  $\pm 1^{\circ}\text{C}$  difference from the nearest logger. Overall our results suggest that water temperatures from a lower reach site in some Gulf of Alaska streams can be representative of main-channel upstream thermal conditions. Watersheds with complex features such as in our

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<sup>2</sup>Meyer, B.M., Wipflfi, M.S., Rinella, D.J., Schoen, E.S., Falke, J.A. Manuscript in prep for *River Research and Applications*.

montane example may be less appropriate for characterizing upstream water temperatures based solely on a single site.

## 2.2 Introduction

Stream thermal regimes are of central influence on habitat of anadromous fish (Brett, 1971). Air temperature is a primary influence on stream water temperature (Mohseni, Erickson, & Stefan, 1998) and water temperatures are predicted to rise over the course of the next century as a result of increasing air temperatures (Wuebbles et al., 2017). Thus measuring and interpreting stream temperatures is essential for understanding influences of climate change on their lifecycle. The improved simplicity and lower costs of instrumentation used for in-situ monitoring of freshwater thermal regimes has led to enormous growth in available datasets, such as NorWeST in the western United States (Isaak et al., 2017) and others. Such datasets have been used to explore questions related to stream thermal sensitivity ( $\Delta^{\circ}\text{C } T_{\text{water}} / ^{\circ}\text{C } T_{\text{air}}$ ) (Caissie, 2006; Morrill, Bales, & Conklin, 2005), develop spatial-stream-network models (Isaak et al., 2014), and examine implications for anadromous habitat (Crozier et al., 2008; Lisi, Schindler, Bentley, & Pess, 2013; Schindler et al., 2008).

In areas with limited or no road access such as coastal Alaska, stream thermal regimes have been commonly monitored at a sole site in a watershed's lower reach – that is, the segment of a watershed nearest to its outlet – to characterize the overall watershed upstream (e.g. Mauger et al., 2017; Winfree et al., 2018; Lisi et al., 2015) as upstream sites can often be challenging to access. Yet watersheds can exhibit substantial spatial thermal heterogeneity as has been documented using longitudinal stream surveys (Vaccaro & Maloy, 2006) and remote sensing (Fullerton et al., 2015; Torgerson, Price, Li, & McIntosh, 1999). The degree of thermal heterogeneity varies among watersheds of different geographic settings, indicating that while some watersheds may benefit from an extensive network of sensors, others may not require as many loggers to assess thermal conditions relevant to a research question. Researchers and managers conscious of logistical and personnel costs associated with logger maintenance and installation are faced with the question of how many sensors are needed for their array, and where to install them. For example, if the intended use of main-channel water temperature data is as daily mean values for input into a fish

growth model (Chapter 1) a watershed likely to have homogenous main-channel daily mean temperatures throughout may benefit less from an extensive water temperature sensor array. The particular research or management question dictates the quantity of loggers needed for in-situ monitoring.

In addition to these considerations related to *longitudinal* thermal variability (Vannote et al., 1980) within stream networks, *lateral* variability between mainstem and off-channel habitats is an important consideration for stream temperature monitoring. Water temperature logger data collected at mainstem sites is commonly used to interpret biological effects on juvenile salmonid populations, but a growing body of evidence suggests that main-channel water temperatures do not fully encompass their actual thermal experience (Armstrong & Schindler, 2013; Limm & Marchetti 2009). For example, juvenile coho salmon consume sources of abundant, energy-dense foods such as salmon eggs (Armstrong et al., 2013) or benthic macroinvertebrates (Baldock, Armstrong, Schindler, & Carter, 2016) in cool habitats then return to warmer off-channel habitats to optimize metabolism. Despite these and other well-documented examples of behavioral thermoregulation, it remains unclear whether it is the exception or the rule among stream-rearing juvenile salmon at high latitudes. If juvenile salmon in a given stream usually occupy temperatures similar to those recorded in the nearby main stem, then this would support the relevance of data collected from mainstem temperature logger installations for applications focused on juvenile salmon. Alternatively, if salmon regularly occupy habitats substantially colder or warmer than the nearby main stem, then interpreting water temperature effects on salmon might benefit from continuing to expand thermal infrared imagery datasets (Dugdale, 2016) and stream temperature monitoring networks focused on salmon might benefit by routinely deploying loggers into lateral habitats.

In this work we aim to provide a framework for understanding when and where a more extensive water temperature sensor network may be appropriate to characterize stream temperature in the Gulf of Alaska region, or when a single site in the lower reach may suffice. We measured summer water temperatures using loggers installed longitudinally throughout three geomorphically distinct tributaries in the Kenai River basin in southcentral Alaska. In addition to the contrast across landscapes, the study

watersheds offer a contrast in the influence of lakes on thermal regime. One of our three study watersheds is interrupted by two major lakes and thus provided an opportunity to examine the type of sensor array needed to account for the discontinuity in stream thermal regimes produced by lakes (Jones, 2010).

Across the lowland-to-glacially influenced gradient of anadromous tributaries found throughout the Kenai River Basin, we assessed the degree to which lower-reach sites were representative of upstream thermal conditions for a) daily descriptors including mean, minimum, and maximum and b) seasonal descriptors of duration, frequency, magnitude, timing, and variability (Arismendi, Johnson, Dunham, & Haggerty, 2013). We hypothesized that thermal regime descriptors in watersheds with high gradients and homogenous input water sources would exhibit little longitudinal variability and be adequately represented by the lower reach site, whereas lower gradient watersheds with heterogeneous inputs would exhibit a more complex thermal pattern and the lower site would be less representative of daily and seasonal thermal regime descriptors. In a watershed with lakes interrupting the main channel, we expected that the lower-reach logger would be strongly correlated with conditions up to the nearest upstream lake outlet, and less correlated at sites above the lake. Across all watershed types, we expected correlations between lower-reach and upstream sites would vary in strength among the five above-mentioned thermal regime descriptor categories. In particular, we anticipated that thermal regime descriptors of variability would be poorly predicted by lower reach logger sites because headwaters areas of streams are more likely to be shallower and flashier relative to lower stream reaches.

Additionally, we explored the degree to which data from mainstem temperature loggers are representative of the thermal experience of juvenile Chinook and coho salmon, i.e. their individual history of temperature environments. We compared instantaneous temperature records from habitats occupied by juvenile Chinook and coho salmon, determined by minnow trap sampling, to the nearest mainstem water temperature logger site. We hypothesized that the majority of records would indicate loggers as generally representative of individual minnow trap locations (within  $\pm 1.0^{\circ}\text{C}$ ), but some percentage of observations would exceed that difference. Lateral thermal heterogeneity; e.g. temperature differences between main-channel locations where

loggers record temperature and bankside or off-channel locations where minnow traps are generally used, can have important metabolic implications for juvenile Chinook and coho salmon as they experience highest growth rates at approximately 15°C but can be substantially lower at higher or lower temperatures (Richter & Kolmes, 2005).

## 2.3 Methods

### 2.3.1 Study Area

The Kenai River drains an area of 5568 km<sup>2</sup> in south-central Alaska, and flows 182 kilometers west from the Kenai mountains to its confluence with Cook Inlet near the city of Kenai (Figure 2.1). We focused monitoring efforts on three geomorphically distinct tributaries of the Kenai River in 2015 and 2016: Beaver Creek (lowland), Russian River (montane), and Ptarmigan Creek (glacial-influenced). Selected landscape characteristics for each of the study tributaries are summarized in Table 2.1. The lowland drainage is characterized as low-elevation and low-gradient and the resulting longer water residence time coupled with early-season snowmelt is associated with higher sensitivity to air temperature and higher average water temperatures (Chapter 1). In contrast, the glacial watershed is characterized as high-elevation, high-gradient, and glacially-influenced (7% glacial surface area coverage). The resulting slow water residence time coupled with late-season snow and glacial melt is associated with low sensitivity to air temperature and lower average water temperatures. The montane watershed was intermediate in all of the attributes of elevation, gradient, glacial coverage. Lakes are present in all of the study watersheds, but only the montane study watershed (Russian River) had major lakes interrupting the main channel of its anadromous extent.

### 2.3.2 Water Temperature Data Acquisition

We monitored water temperature at a minimum of three sites per study tributary along their longitudinal gradients from lower to upper reaches. We recorded data at 15 minute intervals from May to August 2015 and May to September 2016 using automated loggers (HOBO® Temp Pro v2, Onset Corp, Bourne, MA) or Hydrolab sondes (Hydrolab MS-5 Sonde, OTT, Loveland CO). Coordinates and period of

deployment for all sensors are summarized in Appendix 2.1.

We checked all loggers for accuracy using methods outlined in Mauger, Shaftel, Trammell, Geist, and Bogan (2015) prior to and post field deployment. We downloaded data with a HOBO® Waterproof Shuttle at regular intervals (24 - 36 days for the HOBO logger and 10 days for the Hydrolabs) and inspected them for anomalies that would suggest malfunction or exposure to air, and replaced loggers as needed. To fill in data gaps we used data from the nearest available logger if datasets were sufficiently similar: we calculated absolute difference values for all concurrent observations between the two sites and considered them sufficiently similar if overall mean absolute difference was < 0.2°C, which is the same level of precision as the HOBO® TempPro v2 loggers (see Appendix 2.2, Water Temperature Logger Deployment and Maintenance).

We maintained and calibrated Hydrolab probes in a laboratory on a 10-day scheduled interval according to a manufacturer recommended quality assurance plan. Full details on logger maintenance, installation, and retrieval are described in Appendix 2.2.

### **2.2.3 Daily Temperature Descriptors**

We conscribed all water temperature datasets to a common time period of June 1 – August 20 with the exception of Lower Russian River, for which the earliest available record in 2015 was June 22. Three data sets with <60 days observations were excluded (see Appendix 2.1, Figure 2.1A). We summarized water temperature data to daily mean, daily minimum, and daily maximum and linearly regressed each of these values from the lower-reach site of each study drainage against each of its associated upstream sites. For the montane watershed (Russian River), we also regressed daily summary values from the site above the inlet of the lower lake (Middle 1 site) against upstream loggers below the other lake (Middle 2, Upper sites) and above it (Upper 1 site).

### **2.2.4 Seasonal Temperature Descriptors**

We calculated a suite of 39 stream thermal regime seasonal descriptors commonly used to characterize the thermal regimes of streams during summer months using an approach modified from Falke, Dunham, Hockman-Wert, & Pahl (2016) with a

custom script in R (R Core Team, 2019). See Appendix 2.3 for a list of seasonal descriptor definitions and how the descriptors were calculated.

Next, we evaluated the ability of lower-reach sites to predict seasonal descriptors at upstream sites. We calculated standardized difference ( $Z_D$ ) values between lower reach sites and their associated upstream sites with the formula

$$Z_D = \frac{(D_{Upstream\ Site} - D_{Lower\ Reach\ Site}) - Mean}{StDev}$$

where  $D$  was a value of one of the thirty-nine individual thermal regime descriptors for a unique site-year. Mean and standard deviation values are calculated from all lower site vs. upstream site difference values within a unique grouping of descriptor category (magnitude, variability, frequency, timing, or duration) and unit ( $^{\circ}\text{C}$ , count, %, date, or unitless) (see Appendix 2.3, Seasonal descriptors of thermal regime, Table 1). We excluded one descriptor, growing season degree days (GSDD), from PCA analyses due to the large magnitude of difference values for this descriptor relative to other categories. We examined GSDD values separately and regressed its absolute difference values (lower site vs. upstream sites) against upstream distance from the main stem Kenai River.

We performed two separate principal components analyses (PCA) on the same data set of standardized difference values. In the first, we examined dominant patterns of intercorrelation and described the major sources of variation among sites. In the second analysis we examined patterns of intercorrelation among descriptor categories. Because our response variable was standardized, the covariance and correlation matrices were identical. As a result all sites contributed equally to the PCA and were scale independent. We evaluated the statistical significance of PCA axes using the broken-stick method, for which observed eigenvalues are compared with randomly generated values (Jackson, 1993). We ranked sites by thermal regime descriptor category for each significant axis (Table 2.3).

## 2.2.5 Water Temperatures at Minnow Traps

To explore differences between temperatures at fixed logger sites and individual minnow trap locations we recorded instantaneous water temperatures at deployment of Gee ® minnow traps ( $n = 650$  deployments). As part of a concurrent research effort surveying diet and growth of juvenile Chinook (*Oncorhynchus tshawytscha*) and coho (*O. kisutch*) salmon (Chapter 1), we deployed minnow traps on a monthly basis (May – Sept 2015 and 2016) at sites throughout each study drainage. Upon trap deployment we recorded temperatures at the entrance; depths ranged from 15 – 45 cm. We recorded time of measurement to the nearest minute and rounded post-hoc to the nearest quarter hour interval. We used a hand-held Cooper-Atkins AquaTuff Instant Read® Bare Wire thermocouple or YSI® 556 fitted inside a perforated PVC pipe to make point measurements of temperature. Upon each measurement we allowed the reading to stabilize within 0.2 °C. We deployed traps throughout habitat types that included off-channel areas such as side-channels and pools. We excluded trap deployments where no juvenile Chinook or coho salmon were captured from further analysis (total remaining  $n = 426$ ), and identified instances where trap-logger differences exceeded 1°C, 2°C and 4°C.

To verify the ability of the hand-held probe to accurately measure water temperatures in-situ, we compared benthic probe measurements taken adjacent to installed loggers as part of logger deployments, data downloads, and retrievals. For a subset of records ( $n = 38$ , excluding site visits with lentic features or low-flow conditions) we calculated the temperature difference between the logger and the probe measurement. We measured a mean difference of  $0.21 \pm 0.41^\circ\text{C}$  (mean  $\pm$  standard deviation) between the two instruments in-situ, within ~2.0 m of each other, indicating that temperatures measured by the two instruments were comparable within a sub-degree level of precision.

We calculated instream distances between minnow trapping sites and the nearest logger site, and all other instream distance values, using QGIS (QGIS Development Team, 2019) with the Alaska Anadromous Waters Catalog stream shapefile (Blossom & Johnson, 2017). Instream distance between fishing site and

associated water temperature logger ranged from 0 to 4,675 m ( $1,083 \pm 1556$  m, mean  $\pm$  standard deviation) (Appendix 2.1, Table 2.1A).

## 2.3 Results

### 2.3.1 Daily Water Temperature Descriptors

Daily summary values (mean, minimum, and maximum) of water temperature at lower-reach sites were correlated with those at upstream sites (Table 2.2, daily mean temperatures,  $r^2 = 0.72 - 1.0$ , example for Beaver Creek in Figure 2.2). Estimates of slope, intercept, and coefficient of determination were not significantly different among linear regressions that used daily mean, daily minimum, or daily maximum values (coefficient of determination values,  $p = 0.47$ , Kruskal-Wallis; slopes,  $p = 0.86$ , ANOVA; intercepts,  $p = 0.87$ ; ANOVA) and only daily means are described here.

In the montane (Russian River) watershed, loggers within the reach between the two lakes exhibited strong to moderate correlations with the reach's most downstream site (Middle 1), but the relationships were not 1:1. The Middle 2 site exhibited consistently warmer temperatures ( $\text{Middle 2} = -1.3 + 1.2 (\text{Middle 1})$ ,  $r^2 = 0.99$ ) as did the Upper site ( $\text{Upper} = -1.7 + 1.3(\text{Middle 1})$ ,  $r^2 = 0.88$ ), but above Upper Russian Lake the relationship became more uncoupled at the cooler Upper 1 site ( $\text{Upper 1} = 0.1 + 0.52(\text{Middle 1})$ ,  $r^2 = 0.71$ ).

### 2.3.2 Seasonal Descriptor Difference Values: Variation by Site

Thermal regime descriptors measured at lower sites were generally predictive of upstream descriptors in the lowland and glacial-influenced streams, but less so in the montane stream. The lowland and glacial watersheds exhibited relatively close clustering in the PCA plot space while the montane watershed was more dispersed (Figure 2.3A).

Two principal component axes were statistically significant in the PCA analysis in which individual sites/years were plotted. The two axes explained 85% of the variation in how successfully lower sites predicted all seasonal descriptors at an upstream site within a watershed. The first axis (PC I) explained 64% of variation whereas the second axis (PC II) explained 20% of the variation.

### **2.3.3 Seasonal Descriptor Difference Values: Variation by Descriptor**

Thermal regime descriptors measured at lower sites were generally predictive of upstream descriptors for the categories of duration and magnitude, and generally less so for the categories of frequency, variability, and timing. Descriptors of duration and magnitude exhibited relatively tight clustering in the plot space while the other categories are more disperse (Figure 2.3B). Table 2.3 lists the three descriptors in each category with the highest loading values, indicating the three descriptors in each category most representative of each category.

Two principal component axes were statistically significant in the PCA analysis where individual thermal regime descriptors were plotted. The two axes explained 74% of the variation in how an individual seasonal descriptor at an upstream site correlates with its corresponding lower-reach site, across all three study watersheds. The first axis (PC I) explained 47% of variation in how closely descriptor values within a category are correlated with the lower reach site among all streams whereas PC II explained 27%.

### **2.3.4 Growing Season Degree Days**

The magnitude of difference in growing season degree days (GSDD) from the lower site increased with upstream distance. In the Russian River, values at upstream sites differed by as much as -349 to +477 units from the lower site, in Beaver Creek all upstream sites had fewer growing season degree days relative to the lower site ranging from -18 to -288, and in Ptarmigan Creek upstream values relative to the lower site ranged from +28 to -27. We observed a significant positive relationship between upstream distance (km) from the main stem Kenai River and the absolute difference in GSDD from each drainage's lower-reach site (Figure 2.4;  $r^2 = 0.69$ ,  $p = 0.0005$ ).

### **2.3.5 Temperature Variation Between Juvenile Salmon Capture Site and Logger Site**

Water temperatures at minnow trap deployments were generally represented by the nearest logger site; 69% of observations saw absolute differences of  $< 1.0^\circ\text{C}$ . Thirty one percent of all temperature observations at traps exceeded  $\pm 1^\circ\text{C}$  difference from the nearest logger, 14.3% of observations exceeded  $\pm 2^\circ\text{C}$  difference, and 2.5% of observations exceeded  $\pm 4^\circ\text{C}$  difference. All of the  $\pm 4^\circ\text{C}$  difference values were from

three sites; Lower and Upper Russian River (montane), and Middle Ptarmigan Creek (glacial) (Figure 2.5). We found a weak but significant relationship for the instream distance separating fishing sites and logger sites and absolute value of temperature difference ( $r^2 = 0.14$ ,  $p < 0.05$ ), suggesting that instream distance between loggers and traps locations is unlikely alone in accounting for temperature differences.

## 2.4 Discussion

### 2.4.1 Summary

We found support for the hypothesis that water temperature logger data from lower-reach anadromous stream sites were representative of upstream thermal regime characteristics under some conditions. We observed that heterogeneous, montane watersheds were least suitable for characterizing upstream thermal conditions in the main channel based solely on water temperature data from the lower reach. Descriptors of magnitude and duration at upstream sites were well correlated with their associated lower-reach site compared to other thermal regime descriptor categories.

Approximately two-thirds of temperature observations at minnow traps were less than  $\pm 1.0^\circ\text{C}$  different from the nearest logger, indicating water temperatures measured by loggers were representative of thermal conditions at minnow trap locations in most cases.

### 2.4.2 Daily Descriptors

For daily metrics of mean, minimum, and maximum water temperature we observed strong relationships ( $r^2 > 0.7$ ) between the lower and upstream sites. High correlation values indicate there is relatively low variability in the relationships of daily metrics predicted at upstream sites by the lower site. However, the range of slope and intercept values in these relationships indicate that even when high correlation exists, some lower-reach sites are more representative of upstream conditions than others. For example, in the Ptarmigan Creek (glacial) watershed we observed slope values of approximately 1.0 and intercept values  $< 0.5$ , indicating that in this steep, fast, watershed the lower-reach logger is a close representation of upstream main-channel conditions for applications such as the bioenergetics modeling described in Chapter 1.

In the Beaver Creek (lowland) watershed, slopes of temperature relationships between sites were all approximately 0.9, again indicating a consistent relationship. However intercepts for Beaver Creek were < 1.0 at the middle and upper sites, but > 4.0 at the uppermost site. The increasing intercept values indicates warmer daily mean temperatures at upstream sites, a pattern that could be attributed to shallower surface water flow in the area (Fullerton et al.; 2015). Groundwater input is a likely driver of this trend of cooler temperatures downstream, as late-summer snowmelt or glacial input is absent from the low-elevation Beaver Creek watershed.

In contrast to the other two study watersheds, the Russian River (montane) watershed exhibited negative intercept values of less than -2.5 at all upstream sites as well as slopes ranging from < 1 to > 1, indicating a less consistent pattern in terms of the ability of the lower-reach logger to predict upstream daily mean temperatures. These data indicate on some days daily mean water temperature is cooler upstream while on other days it is warmer. A combination of factors likely drives this trend including heterogenous late-season snowmelt and warm lake water inputs throughout the watershed. The coolest site in the Russian River watershed was the uppermost site (Upper 1), which was situated at the inlet to Upper Russian Lake close to the small glaciated portion of the watershed.

Our results suggest practical implications for those planning to deploy a stream temperature sensor array. For research questions that involve daily inputs of water temperature summary values such fish growth models, in watersheds similar to Ptarmigan Creek (glacial) with a relatively smaller area, constrained valley, and high gradient, a dataset from the lower reach may be sufficient to represent main-channel lotic temperatures throughout much of the watershed. In watersheds with similar physiography to our Beaver Creek (lowland) example where gradient was lower and valley shape was less constrained, it may not be appropriate to characterize upstream conditions based on the lower-reach thermal regime without information on the degree to which upstream temperatures are consistently higher or lower. If installing a more extensive sensor network is not feasible in these watershed types, characterizing instantaneous temperature at upstream sites several times throughout the logger's deployment could offer critical perspective on longitudinal heterogeneity within the

watershed. In the Russian River (montane), we observed that using the lower-reach thermal regime to characterize daily summary values upstream is less suitable as thermal heterogeneity throughout makes prediction impractical. Watersheds with potentially similar levels of thermal heterogeneity, for example those with lakes interrupting the main channel, are thus most valuable for more extensive sensor networks and as potential targets for acquiring aerial thermal imagery data, and for interpreting temperature data from lower-reach sites with moderation. The discontinuity in stream thermal regime produced by lakes suggests that at minimum, a logger site located above each lake inlet to characterize the upstream reach would provide a greatly more thorough representation of thermal regime. However, even within the reach between Lower and Upper Russian lakes, we observed warmer temperatures as upstream distance increased (Table 2.2), indicating that in this case the single logger above the lower lake outlet would not fully characterize the reach. In heterogeneous environments like this a downstream floating longitudinal temperature profile as described in Vaccaro et al. (2006) could be a cost-effective and efficient way to characterize main-stem thermal heterogeneity

#### **2.4.3 Seasonal Thermal Regime Descriptors**

The degree to which lower-reach sites successfully predicted thermal regime descriptors at upstream sites varied by watershed and by descriptor category. Close clustering within the plot space of Figure 2.3A, as observed for Ptarmigan Creek (the glacial-influenced stream), indicates that generally little difference existed in descriptor values between the lower site and upstream sites. A dispersed plot space, as observed for the Russian River (the montane stream), indicates that descriptor values have greater likelihood of having a high absolute difference between the lower site and upstream sites.

Some categories of seasonal descriptors such as duration (measures of annual mean, minimum, and maximum) and magnitude (measures of exceedance of a given temperature value) exhibited relatively tight clustering in the plot space (Figure 2.3B), indicating that for these categories descriptors at upstream sites were of similar value to the downstream site. Conversely, descriptors of frequency (cumulative observations exceeding a given temperature value), variability (measures of variance), and timing

(when observations of a temperature value occur, e.g. hottest day of the summer) were more disperse indicating that values of descriptors in these categories are more likely to diverge widely from the lower-reach site.

Growing season degree days (GSDD), a metric widely used to assess influence of thermal conditions on development of ectothermic organisms (Alderdice and Velsen 1978), was correlated with upstream distance from the main stem Kenai River ( $r^2 = 0.69$ ,  $p = 0.0005$ ). As upstream distance from the main stem grew absolute difference values in GSDD from the lower reach site also grew, because water temperatures were less integrative of the overall watershed and more likely to reflect local influences (Vannote, Minshall, Cummins, Sedell, & Cushing, 1980). For example, the Upper Russian 1 site at the inlet to Upper Russian Lake and close to the small glaciated portion of the watershed was much colder than the lower site. In contrast, the Upper Russian site below the outlet of Upper Russian Lake was much warmer relative to the lower-reach site, as the influence of the lake increased main channel water temperatures in this area. GSDD values from lower-reach sites should in general expected to be increasingly uncoupled from upstream conditions as upstream distance increases.

Our results indicate that when seeking to account for stream thermal heterogeneity, some watersheds may benefit more than others from a more extensive water temperature sensor network, high-resolution thermal imagery data, or statistical spatial modeling efforts. In watersheds with broadly similar geomorphic characteristics as the Russian River (montane) example here, such as abundant off-channel habitat and heterogeneous inputs of cool (e.g. snow and glacial melt) and warm (e.g. lakes) water sources, management and conservation efforts may benefit more than the other two watershed types examined in this study from these more spatially detailed characterizations. For the question of how many logger sites are needed, at minimum a site above the inlet of each lake interrupting the main channel in the areas of interest will create a much more representative picture as this strategy would account for the discontinuity in thermal regimes produced by lakes. Lower-reach datasets from watersheds more likely to exhibit thermal heterogeneity throughout (e.g. similar to the Russian River example) are unlikely to fully represent thermal experience of resident

biological organisms, particularly for organisms that move among thermal habitats such as juvenile salmonids. However in these environments lower-reach temperature data is still critical for applications such as in-season interpretation of upstream migration timing of adult anadromous fish including salmon (Keefer, Peery, & Caudill, 2008; Lisi et al., 2013).

#### **2.4.4 Thermal Experience at Juvenile Salmon Capture Sites and Logger Sites**

We observed that while water temperatures at logger sites can differ substantially from those at individual minnow traps, most observations (69%) were within  $\pm 1^{\circ}\text{C}$  from the nearest logger. With an average distance between trap and logger of 1 km such differences are not unanticipated. In the Russian River (montane) we found trap temperature observations of  $\geq 4^{\circ}\text{C}$  absolute difference from the nearest logger at all fish sampling sites. Temperature differences of this magnitude can have important implications for juvenile Chinook and coho salmon growth, as a shift of  $\pm 2$  to  $4^{\circ}\text{C}$  can shift thermal conditions either towards or away from optimal metabolic efficiency (Beauchamp, 2009).

Study of behavioral thermoregulation among different thermal conditions relies on tracking movement among environments in a limited spatial setting because technology does not yet exist to integrate continuous temperature loggers within fish tags suitable for freshwater juvenile salmonids (fork length  $< 120$  mm). Otolith analysis, another technique used to explore relationships between growth and temperature, can also reveal coarser patterns of how thermal experience influences growth (Chittaro, Zabel, Haught, Sanderson, & Kennedy, 2014). Until fish tag technology is sufficiently miniaturized, our understanding of thermal experience at broader population scales is based on such studies. Thermal heterogeneity thus complicates interpretation of how climate-driven changes in thermal regime affect thermal experience of stream-resident juvenile salmonids.

#### **2.4.5 Management Applications**

When planning to install and maintain water temperature sensor arrays, researchers should consider the specific data application in choosing an appropriate

distribution of sensors. Some research questions may benefit from a more extensive sensor array while for other projects cost of doing so may outweigh benefits.

Research questions that involve thermal regime descriptors of frequency (how often a temperature threshold is exceeded), variability (the spread of temperature observations within a given time period), and timing (e.g., the hottest day of the summer) of temperature may demand a more spatially granular approach for understanding main-channel water temperature heterogeneity. Conversely, research questions that require daily values for water temperature (e.g. studies focused on the potential of stream habitats to support fish growth or vulnerability to impacts of thermally constrained invasive species) may not necessarily require continuous water temperature data from throughout a stream extent to estimate main channel temperatures, depending on the watershed's geomorphic characteristics. Spatial statistical network models based on remote sensing as well as in-situ data, particularly valuable for research questions that involve comparing thermal regimes throughout a watershed or under different hydrological or climate scenarios, offer a robust avenue for estimating water temperatures used for biological modeling efforts (Chittaro et al., 2014; McNyset, Volk, & Jordan, 2015; Peterson et al., 2013; Siegel & Volk, 2019) but can take substantial technical expertise and field data to design and validate.

Characterizing finer-scale water temperature heterogeneity continues to be essential for conservation of thermal refugia (Isaak, Young, Nagel, Horan, & Groce, 2015), particularly in regions currently seeing rapid development in or near riparian areas (Cook Inletkeeper, 2010). Watersheds with abundant off-channel habitat and heterogeneous inputs of cool (e.g. snow and glacial melt) and warm (e.g. lakes) water sources, such as the Russian River example here, may be most appropriate for focusing efforts to acquire high-resolution aerial infrared imagery and other characterizations of thermal diversity used for prioritizing conservation efforts.

## 2.5 Acknowledgments

This study was funded by the Alaska Established Program to Stimulate Competitive Research (Alaska EPSCoR) NSF award #OIA-1208927 with matching funds from the state of Alaska, and was completed in partial fulfillment of an M.S. degree in fisheries. Funding was also provided by an Institute of Arctic Biology Summer

Graduate Research Award, Nicholas Hughes Memorial Scholarship, and the University of Alaska Department of Biology and Wildlife. Administrative support was provided by the Alaska Cooperative Fish and Wildlife Research Unit, University of Alaska College of Fisheries and Ocean Sciences, and Institute of Arctic Biology. We followed IACUC approved protocols (#720490-4) and Alaska Department of Fish and Game Fish Use Permit requirements (SF2015-191 and SF2016-158) to ensure proper animal handling care and precautions. Technicians Emily Neideigh and Christina Mielke provided substantial field and laboratory support. In-kind support was provided by the Kenai Watershed Forum, Cook Inletkeeper, and Kenai Peninsula College. Thanks to volunteer local support in the Kenai area from John and Molly Messick and Dave and Kathy Wartinbee, to Zach Baer and Dr. Leslie Jones for GIS assistance, and numerous other volunteers. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government. The findings and conclusions in this article are those of the authors and do not necessarily represent the views of the U.S. Fish and Wildlife Service. Data used in this study is available from the KNB (Knowledge Network for Biocomplexity) repository at doi:10.5063/F1Q52MZF.

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## 2.7 Tables

**Table 2.1.** Table of landscape characteristic values for tributaries derived from USGS 1 m Digital Elevation Map (USGS, 2016) and the National Hydrography Dataset (USGS, 2016).

Watershed	Elevation at mouth (m)	% Ice Cover in Water-shed	Meets with Main Stem of Kenai (km)	Average Gradient (%)	Water-shed Area (km <sup>2</sup> )	Total Length (km)
<b>Lowland (Beaver Creek)</b>	0	0%	17	2%	157	58
<b>Montane (Russian River)</b>	106	<1%	121	9%	163	90
<b>Glacial (Ptarmigan Creek)</b>	133	7%	165	14%	86	43

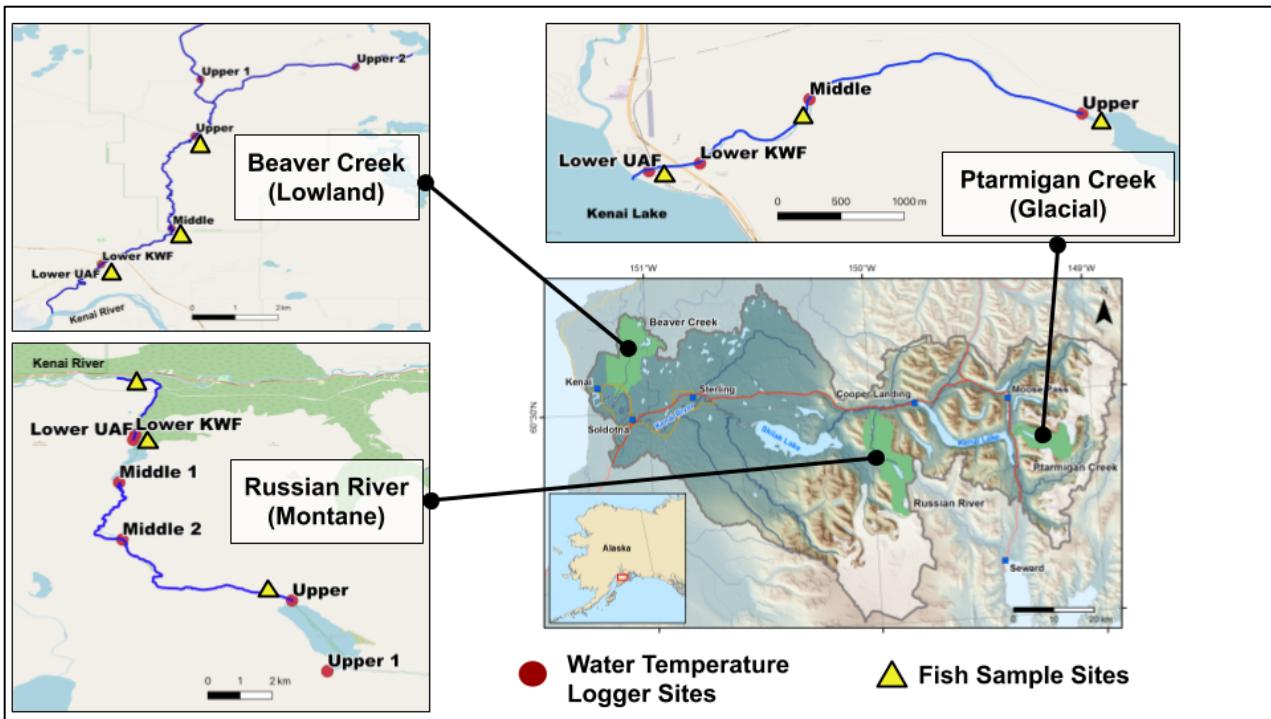
**Table 2.2.** Slope, intercept, and coefficient of determination ( $r^2$ ) estimates from linear regressions of daily mean temperatures from lower-reach water temperature sites on associated upstream sites. Estimates were not significantly different for linear regressions using daily minimum or maximum values ( $r^2$  values,  $p = 0.47$ , Kruskal-Wallis; slopes,  $p = 0.86$ , ANOVA; intercepts,  $p = 0.87$ ; ANOVA).

Stream Name	Upstream Site	Intercept		Slope		Overall
		Estimate $\pm$ StDev	p-value	Estimate $\pm$ StDev	p-value	
Lowland (Beaver Creek)	Middle	0.55 $\pm$ 0.12	< 0.01	0.93 $\pm$ 0.01	< 0.01	0.98
	Upper	0.89 $\pm$ 0.18	< 0.01	0.91 $\pm$ 0.01	< 0.01	0.95
	Upper 2	4.43 $\pm$ 0.47	< 0.01	0.92 $\pm$ 0.04	< 0.01	0.85
Montane (Russian River)	Middle 1	-2.73 $\pm$ 0.72	< 0.01	1.37 $\pm$ 0.07	< 0.01	0.78
	Middle 2	-4.64 $\pm$ 0.88	< 0.01	1.61 $\pm$ 0.08	< 0.01	0.77
	Upper	-6.09 $\pm$ 0.9	< 0.01	1.82 $\pm$ 0.08	< 0.01	0.85
	Upper 1	-3.54 $\pm$ 0.33	< 0.01	0.92 $\pm$ 0.03	< 0.01	0.89
Glacial (Ptarmigan Creek)	Middle	-0.12 $\pm$ 0.06	0.03	1.01 $\pm$ 0.00	< 0.01	1.00*
	Upper	-0.56 $\pm$ 0.2	< 0.01	1.03 $\pm$ 0.02	< 0.01	0.95

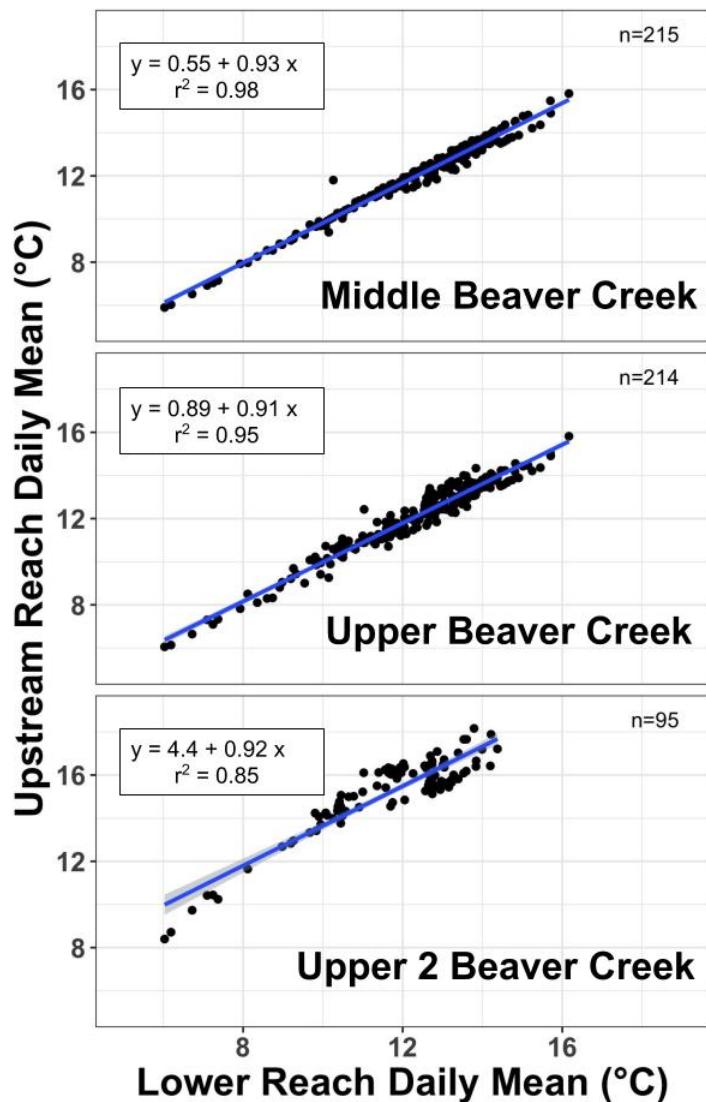
\* Value rounded up from 0.999

**Table 2.3.** Top three stream temperature descriptors with the largest absolute loadings for each significant principal component (PC I and PC II) by category. Descriptors with the largest absolute loadings across both principal components are also presented (Overall column). The eigenvalues and percentage of variance are shown for each significant principal component and the total. See Appendix 3, Table 1 for the definitions of descriptor abbreviations.

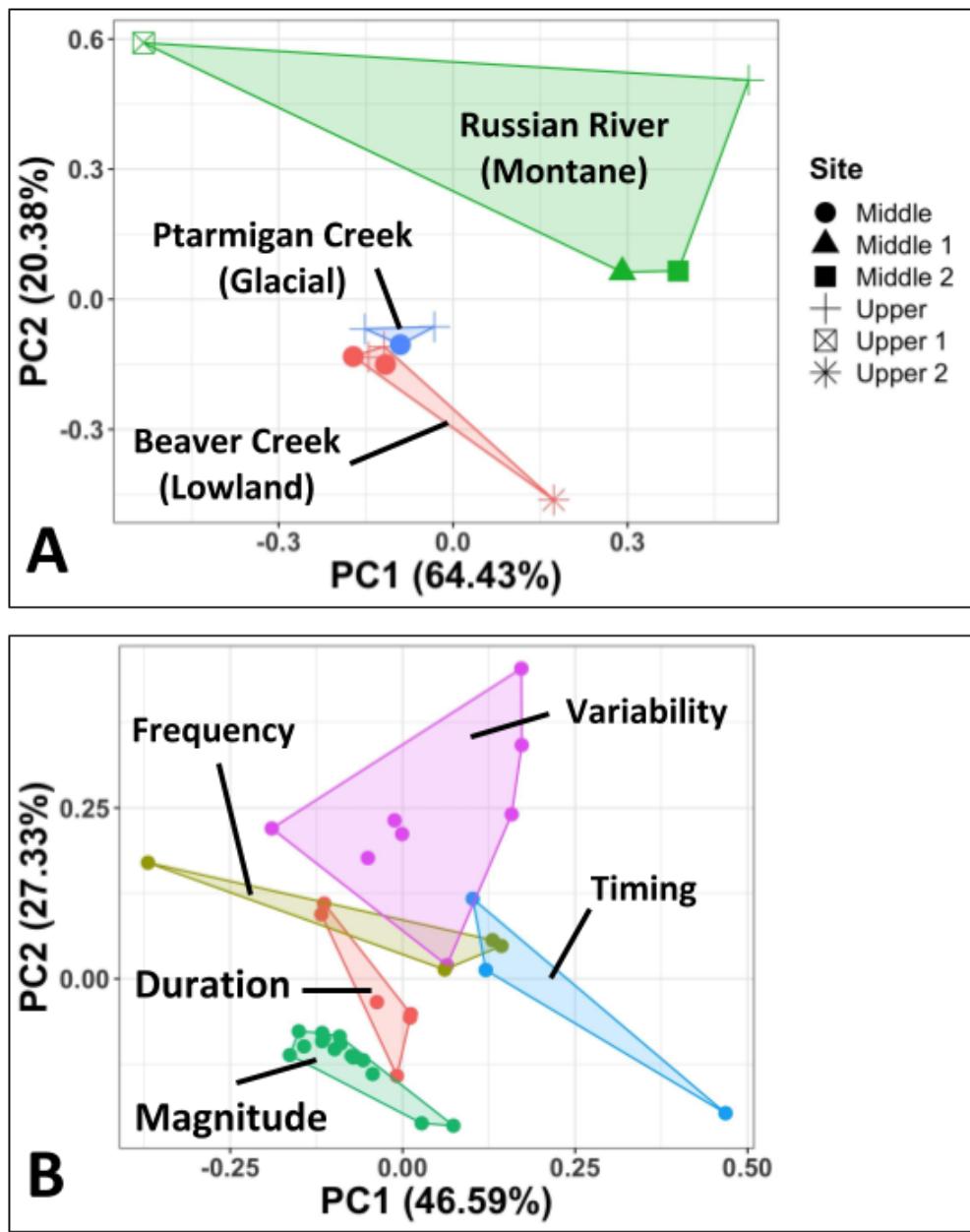
Category	PC1	PC2	Overall
Duration	DMOV15	DMOV15	DMOV15
	DMAX15	DMAX15	DMAX15
	PG10	PG10	PG10
Frequency	SUM_14	SUM_14	SUM_14
	SUM_18	SUM_18	SUM_18
	WEEK_18	WEEK_18	WEEK_18
Magnitude	MDMT	MAT	OVER_MIN
	MWAT	WMT5	MDMT
	MOV	OVER_MIN	WMT5
Timing	MIN_DATE	MIN_DATE	MIN_DATE
	MIN_DATE_ROLL	MIN_DATE_ROLL	MIN_DATE_ROLL
	MDMT_DATE_ROLL	HOTWEEK	HOTWEEK
Variability	RNG	RNG	CV_MIN
	SIGMA_MAX	CV_MIN	CV_MN
	SIGMA_MN	CV_MN	RNG
Eigenvalue	25.42	8.04	
Proportion Explained	0.64	0.20	



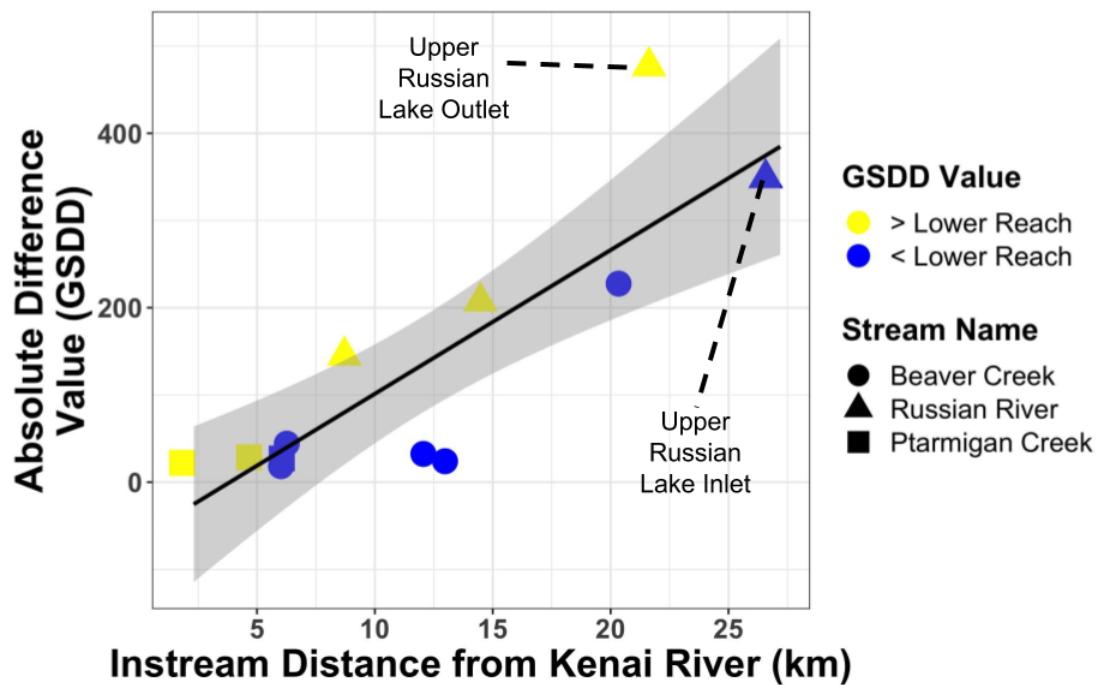
**Figure 2.1.** Map of Kenai River watershed with study tributaries and fish sampling sites highlighted. Beaver Creek is characterized as low elevation and low gradient and Ptarmigan Creek as high elevation and high gradient, with the Russian River representing an intermediate of these attributes. Modified version of main stem Kenai River map previously published in Schoen et al. (2017).



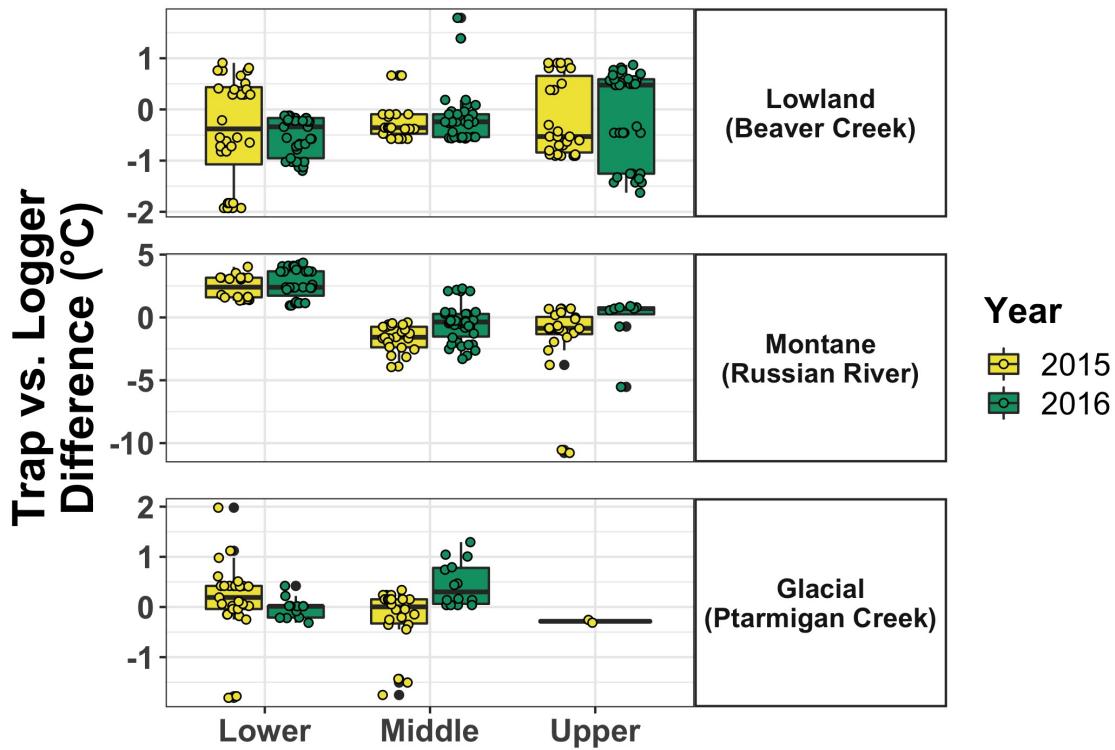
**Figure 2.2.** Example from Beaver Creek of linear regressions for June 1 - Aug 20 daily mean water temperature ( $^{\circ}\text{C}$ ) at Lower vs. upstream sites. See Table 2 for full results of regression parameter values from all watersheds.



**Figure 2.3.** Principal component analysis (PCA) plots of difference values (lower-reach site vs. upstream site) of 39 seasonal thermal regime descriptors, standardized by descriptor category and unit.



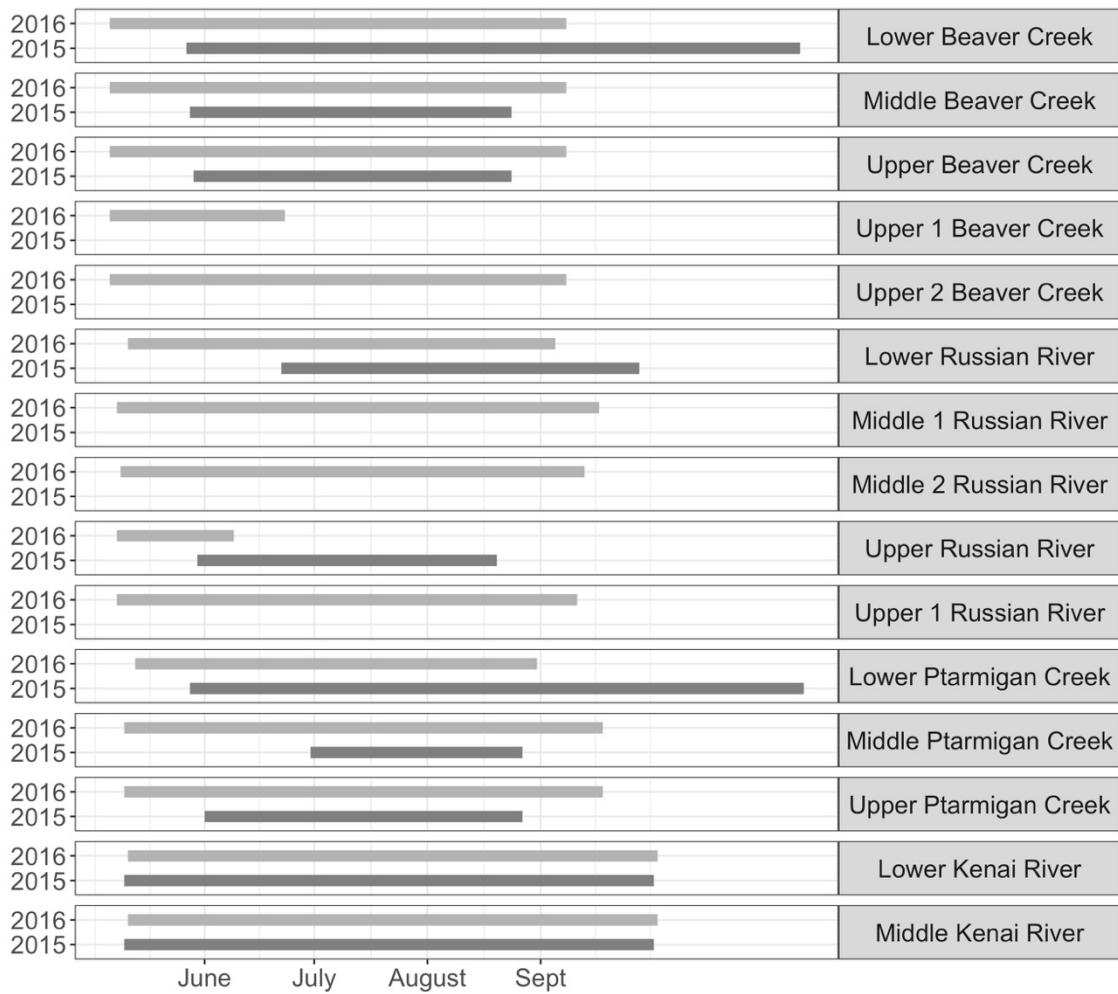
**Figure 2.4.** Distance upstream from the Kenai River main stem vs. absolute difference in growing season degree days (GSDD) between logger site and its drainage's lower-reach site ( $r^2 = 0.69$ ,  $p = 0.0005$ ).



**Figure 2.5.** Temperature difference values; each point represents a difference value between an individual minnow trap and the nearest logger site. Values  $> 0$  indicate the trap site was warmer than the logger site and values  $< 0$  indicate the tap site was cooler than the logger site. Data from 2016 are absent from Upper Ptarmigan Creek because target species were absent in an initial visit. Instream distances from logger sites to associated fish sampling sites are in appendix table 2.1A. Note different y-axis ranges for each of the three watersheds.

## 2.8 Appendices

### Appendix 2.1. Logger Sites and Deployment Extent



**Figure 2.1A.** Duration of available water temperature data by site and year.

**Table 2.1A.** Locations of water temperature loggers and minnow trapping sites, with distances upstream from main stem Kenai River.

River	Reach	Fishing Site		Water Temperature Logger		Water Logger Agency	Kenai Main Stem (m)	Instream Distance, Site to Water Logger (m)
		N	W	N	W			
Lowland (Beaver Creek)	Lower	60.560500	-151.125556	60.560500	-151.125556	KWF	3418.4	18.2
	Middle	60.570139	-151.103444	60.575639	-151.095750	UAF	6591.2	1192.0
	Upper	60.615139	-151.086194	60.615083	-151.085972	UAF	12670.4	6.5
Montane (Russian River)	Upper 2	NA	NA	60.644700	-151.017550	UAF	NA	NA
	Lower	60.484611	-149.993639	60.453000	-149.986767	KWF	4844.1	4675.3
	Middle	60.450028	-149.987472	60.453000	-149.986767	KWF	5137.7	42.8
	Middle 1	NA	NA	60.426100	-149.95820	UAF	NA	NA
	Middle 2	NA	NA	60.391360	-149.991560	UAF	NA	NA
	Upper	60.368250	-149.934889	60.359500	-149.898722	UAF	22260.8	2299.4
Glacial (Ptarmigan Creek)	Upper 1	NA	NA	60.319560	-149.878880	UAF	NA	NA
	Lower	60.403750	-149.369806	60.404833	-149.362317	KWF	624.1	432.9
	Middle	60.409472	-149.356833	60.414056	-149.346639	UAF	2317.1	1078.8
	Upper	60.411528	-149.305639	60.412000	-149.307611	UAF	5220.5	0.0

UAF ~ University of Alaska Fairbanks, KWF ~ Kenai Watershed Forum, USGS ~ United States Geological Survey

## **Appendix 2.2.** Water Temperature Logger Deployment and Maintenance

### *Water Temperature Logger Sites*

To ensure that water temperature logger sites were not influenced by local thermal anomalies, we selected well-mixed sites in accordance with standards published in Mauger, Shaftel, Trammell, Geist, and Bogan (2015). At each site we placed loggers in the mid-center region of the mainstream channel in a location that was (1) adequately mixed, (2) in an un-shaded region, and (3) on the benthic surface of the stream. To ensure that the location was well mixed (varied  $< 0.25^{\circ}\text{C}$ ) we took at least ten measurements (5 surface and 5 benthic) in a shore to shore transect of the stream using a Cooper-Atkins AquaTuff Instant Read® Bare Wire thermocouple. We repeated the transect at all events of deployment, check, and removal. We placed loggers at locations not influenced by point sources such as: ground water, lake outlets, or placed in a position such that the transparent base of the temperature logger became vertically oriented and exposed to direct sunlight. We anchored loggers to the stream bed using metal rebar stakes and programmed to record temperatures at 0.25 h intervals. Data recorded at each site visit included latitude and longitude, photographs (upstream, downstream, and across the transect), instantaneous water temperatures, and date and time of placement.

### *Merging Data from Multiple Sites*

Due to exposed or malfunctioning loggers some water temperature datasets had missing intervals. In order to achieve continuous datasets, we evaluated nearby sites as potential sources of replacement data. We considered datasets sufficiently similar for merging if annual mean difference was  $< 0.2^{\circ}\text{C}$ . Extent of logger deployment and composition of final datasets is summarized in Figure 2.1A.

We combined data at lower reach sites where multiple agencies (University of Alaska or Kenai Watershed Forum) monitored temperature when possible (mean absolute difference of all concurrent values  $< 0.2^{\circ}\text{C}$ ) to create the longest and most continuous data set. We excluded data series with time extent less than sixty days in analyses of daily and seasonal descriptors as they were not of comparable time periods

to all other sites/years. Excluded data sets include Upper Russian River 2016, Middle Ptarmigan Creek 2015, and Upper Beaver Creek 1 2016.

## Appendix 2.3. Seasonal Descriptors of Thermal Regime

**Table 2.3A.** Thermal regime descriptors and definitions (from J. A. Falke, Dunham, Hockman-Wert, and Pahl (2016)).

Descriptor Acronym	Description	How to calculate	Category	Units
MDAT <sup>1</sup>	Mean daily average temperature	The highest average temperature summarized one calendar day during the summer	Magnitude	°C
MDMT <sup>1</sup>	Maximum daily maximum temperature	The highest instantaneous maximum temperature recorded during the summer	Magnitude	°C
MWMT <sup>1</sup>	Maximum weekly average maximum temperature	The highest average temperature summarized over a continuous 7 days during the summer	Magnitude	°C
MWAT <sup>1</sup>	Maximum weekly average temperature	The highest average maximum temperature summarized over each day of a continuous 7 days during the summer	Magnitude	°C
AWAT <sup>1</sup>	Average weekly average temperature	The average temperature recorded across all observations from 1 July through 20 August	Magnitude	°C
GSDD <sup>2</sup>	Cumulative degree-days	Sum of daily mean temperatures	Magnitude	°C
OVER_MIN <sup>3</sup>	Overall minimum temperature during the summer	Overall minimum temperature during the summer	Magnitude	°C
MAT*	Mean annual temperature	The average daily temperature over a year	Magnitude	°C
WMT5 <sup>2</sup>	The 5th percentile of the weekly mean temperatures	The 5th percentile of the weekly mean temperatures	Magnitude	°C
WMT25 <sup>2</sup>	The 25th percentile of the weekly mean temperatures	The 25th percentile of the weekly mean temperatures	Magnitude	°C
WMT50 <sup>2</sup>	The 50th percentile of the weekly mean temperatures	The 50th percentile of the weekly mean temperatures	Magnitude	°C
WMT75 <sup>2</sup>	The 75th percentile of the weekly mean temperatures	The 75th percentile of the weekly mean temperatures		
WMT95 <sup>4</sup>	The 95th percentile of the weekly mean temperatures	The 95th percentile of the weekly mean temperatures	Magnitude	°C
MOV <sup>2</sup>	Maximum value of the moving seven-day mean daily maximum	The moving seven-day mean daily maximum for a specific day is the mean of the daily maximums for the day, the three days prior to the day, and the three days following the day	Magnitude	°C
MMAX <sup>2</sup>	Mean of all daily maximum temperatures	The mean of all daily maximum temperatures for the entire dataset	Magnitude	°C
MMIN <sup>2</sup>	Mean of all daily minimum temperatures	The mean of all daily minimum temperatures for the entire dataset	Magnitude	°C

**Table 2.3A.** Thermal regime descriptors and definitions (from J. A. Falke, Dunham, Hockman-Wert, and Pahl (2016)).

Descriptor Acronym	Description	How to calculate	Category	Units
MMOV <sup>2</sup>	Mean of all seven-day mean daily maximum temperatures	Mean of all moving seven-day mean daily maximum temperatures	Magnitude	°C
DELTA_MAX*	Maximum daily temperature range	Maximum daily temperature range	Variability	°C
SIGMA_MN <sup>3</sup>	Variance of summer daily mean temperatures	Variance of summer daily mean temperatures	Variability	°C
SIGMA_MIN <sup>3</sup>	Variance of summer daily minimum temperatures	Variance of summer daily minimum temperatures	Variability	°C
SIGMA_MAX <sup>3</sup>	Variance of summer daily maximum temperatures	Variance of summer daily maximum temperatures	Variability	°C
CV_MN <sup>3</sup>	Coefficient of variation of summer daily mean temperatures	Coefficient of variation of summer daily mean temperatures	Variability	Unitless
CV_MIN <sup>3</sup>	Coefficient of variation of summer daily minimum temperatures	Coefficient of variation of summer daily minimum temperatures	Variability	Unitless
CV_MAX <sup>3</sup>	Coefficient of variation of summer daily maximum temperatures	Coefficient of variation of summer daily maximum temperatures	Variability	Unitless
RNG <sup>2</sup>	Difference between the MAX and MIN	Difference between the highest temperature and lowest temperature of the year	Variability	°C
WEEK_14 <sup>1</sup>	Cumulative days maximum greater than 14C during the hottest week	Cumulative days maximum greater than 14C during the hottest week	Frequency	Count
WEEK_18 <sup>1</sup>	Cumulative days maximum greater than 18C during the hottest week	Cumulative days maximum greater than 18C during the hottest week	Frequency	Count
SUM_14 <sup>1</sup>	Cumulative days maximum greater than 14C during entire summer	Cumulative days maximum greater than 14C during entire summer	Frequency	Count
SUM_18 <sup>1</sup>	Cumulative days maximum greater than 18C during entire summer	Cumulative days maximum greater than 18C during entire summer	Frequency	Count
DMOV10 <sup>2</sup>	Number of days that the moving seven-day mean daily maximum exceeded 10C	Number of days that the moving seven-day mean daily maximum exceeded 10C	Duration	Count
DMOV15 <sup>2</sup>	Number of days that the moving seven-day mean daily maximum exceeded 15C	Number of days that the moving seven-day mean daily maximum exceeded 15C	Duration	Count

**Table 2.3A.** Thermal regime descriptors and definitions (from J. A. Falke, Dunham, Hockman-Wert, and Pahl (2016)).

Descriptor Acronym	Description	How to Calculate	Category	Units
DMAX10 <sup>2</sup>	Number of days that the daily maximum exceeded 10C	Number of days that the daily maximum exceeded 10C	Duration	Count
DMAX15 <sup>2</sup>	Number of days that the daily maximum exceeded 15C	Number of days that the daily maximum exceeded 15C	Duration	Count
PG10 <sup>2</sup>	Percentage of all temperatures that exceed 10C	Percentage of all temperatures that exceed 10C	Duration	%
PG15 <sup>2</sup>	Percentage of all temperatures that exceed 15C	Percentage of all temperatures that exceed 15C	Duration	%
MDMT_DATE*	Date of instantaneous maximum temperature	Date of instantaneous maximum temperature	Timing	Date
MDMT_ROLL*	Date of highest 7-day running mean of daily maximum temperature	Date of highest 7-day running mean of daily maximum temperature	Timing	Date
MIN_DATE*	Date of instantaneous minimum temperature	Date of instantaneous minimum temperature	Timing	Date
MIN_ROLL*	Date of highest 7-day running mean of daily maximum temperature	Date of highest 7-day running mean of daily maximum temperature	Timing	Date
HOTWEEK*	Midpoint of week with the highest average	Midpoint of week with the highest average	Timing	Date

<sup>1</sup>Dunham, Chandler, Rieman, and Martin (2005), <sup>2</sup>Arismendi et al. (2013) , <sup>3</sup>Garnett (2002),

<sup>4</sup>Hillman et al. (1999), \*Falke et al. (2016).

## **General Conclusions**

Climate warming in south-central Alaska is anticipated to alter temperature and discharge of anadromous streams throughout the Gulf of Alaska region (Leppi et al. 2014; Prucha 2011). Our results in chapter one indicate that climate change-driven impacts to early life history of stream-resident juvenile salmon, such as shifts in smolt outmigration timing, may be experienced earliest and most pronounced in low-elevation, low-gradient streams. The results contribute to growing evidence that juvenile salmon habitat is influenced differently on the basis of local landscape setting and underscores the importance of a portfolio of heterogeneous habitats in mediating the sensitivity to climate change. The intra-species life history diversity generated throughout a large, varied watershed may provide resilience against incoming potential phenological mismatches (Carr-Harris et al. 2018).

In chapter two, our results indicate that watershed types with similar to our Russian River (Montane) example, with abundant off-channel habitat and heterogeneous inputs of glacial and snow melt, exhibit the greatest level of thermal heterogeneity relative to other tributaries considered in this study. Acquiring high-resolution thermal imagery data and developing remote-sensing based statistical models for watersheds with similar characteristics (i.e. lakes interrupting the main stem, heterogeneous inputs of glacial and snow melt), particularly in developing areas, is apparent as a priority in the data-intensive work of mapping thermal habitat diversity.

Our growth simulation results predict decreased juvenile Chinook and coho salmon growth rates under future climate and diet scenarios in almost all habitat settings in our study systems of the Kenai River watershed. Interpreting the ultimate effect that this trend could have on mean smolt size at outmigration requires further evaluation. Widening of the shoulders of ice-free seasons, a likely trend not modeled in this study, has the potential to counteract the effect of reduced growth rates by allowing for an extension in period of temperature conditions conducive to growth. Assuming that climate-driven changes to growth rate do affect size and age class composition of out-migrating smolts, the effect of

this trend on overall population productivity can be challenging to detect (Graham et al. 2019). Recent analyses of long-term data in the Bristol Bay region has generally found warming trends as a driver of earlier outmigration that produces smaller, younger sockeye smolts that did not correlate with overall population productivity (Tillotson and Quinn 2016), but along with other stressors can simplify age-class structure that provides stability to the population (Cline et al. 2019).

The contrast to our own simulation results, which instead found simulated decreases in growth rates as future waters warm, likely arises from different thermal regimes in the Kenai tributaries studied here vs. those studied in the Bristol Bay region. Water temperature monitoring techniques differed between our study and the Bristol Bay region studies referenced, but in general the Bristol Bay studies employed summer water temperatures that were several degrees Celsius cooler than those we observed in the Kenai. Juvenile salmon populations rearing in temperatures below physiological optimum of 12 - 17°C (Beauchamp et al. 2007) would see increased growth rates as water temperatures rise, whereas those currently rearing in temperatures at or above physiological optimum would see growth rates decrease. Together, these studies highlight that our understanding of how climate change is influencing salmon populations is best interpreted as specific to a particular region and population.

The degree to which juvenile salmon may or may not be able to adapt to climate change-induced shifts in their habitat quality and structure remains a topic of ongoing investigation. If potential for physiological adaptation to maximum thermal tolerance in juvenile Chinook salmon is limited (Muñoz et al. 2015), then without climate mitigation there is a high likelihood of loss of many wild populations in the 21<sup>st</sup> century. However our results in chapter one demonstrate that the magnitude of effects from warming thermal regimes will vary among populations and habitat types (Crozier and Zabel 2006), and recognizing this diversity is important to accurately assess risks. A diverse portfolio of habitat types and life histories among and within Pacific salmon populations may offer the most valuable buffer against habitat disruption by climate change, in which case conservation and restoration of anadromous habitat would be an essential

management strategy to ensure long-term viability of wild salmon populations (Mantua et al. 2015).

Our results from chapter two highlight the value of considering specific applications of water temperature prior to establishing monitoring sites. Long-term continuous water temperature data sets are among the most important in documenting aquatic habitat changes, and its acquisition and application can be simplified by understanding the spatial and temporal features of thermal regime relevant to a particular question. Additionally, our comparison of minnow trap temperatures relative to logger temperatures emphasizes the importance of accounting for thermal heterogeneity when interpreting effects of temperature on juvenile salmonids. While main-channel water temperatures may more closely represent thermal experience in our lowland (Beaver Creek) and glacially-influenced (Ptarmigan Creek) stream examples, it is clear that in our montane (Russian River) example that water logger temperature data is a point measurement that does not necessarily encompass thermal experience of juvenile salmon.

The changes brought by climate warming discussed in this research may be arriving much sooner than anticipated by global air temperature models employed in our simulations. The year 2019 saw record breaking temperatures throughout Alaska, including the Kenai Peninsula (Di Liberto 2019). Stream water temperature metrics projected for the 2060-2069 period, including Maximum Weekly Maximum Temperature (MWMT), were observed in summer 2019 throughout south central Alaska, nearly a half century in advance of original predictions (Mauger 2019). Observation of these water temperatures should give context to the rapid pace of habitat shifts currently underway. As air temperatures continue to increase in Alaska, conservation of thermal diversity at multiple landscape scales will be essential to maintain the variability of timing and development in early life stages of wild salmon populations.

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## Appendices

### Appendix A. 2015 Fish Resource Permit



STATE OF ALASKA  
DEPARTMENT OF FISH AND GAME  
333 Raspberry Road  
ANCHORAGE, ALASKA 99518

Permit No. SF2015-191

Expires: 12/31/2015

FISH RESOURCE PERMIT  
(For Scientific/Collection Purposes)

**This permit authorizes:**

**Benjamin Meyer**

(whose signature is required on page 3 for permit validation)

Of

University of Alaska Fairbanks  
902 Koyukuk Drive, Room 207, Fairbanks, AK 99775  
(907) 232-0280 bemeyer@alaska.edu

to conduct the following activities from May 21, 2015 to December 31, 2015 in accordance with AS 16.05.930 and AS 16.05.340(b).

**Purpose:** To assess the impacts of climate change on juvenile coho and king salmon growth potential from Kenai River tributaries of differing hydrologic settings.

**Location:** Beaver Creek (244-30-10010-2025), Ptarmigan Creek (244-30-10010-2231), and Russian River (244-30-10010-2158)

**Species:** Coho salmon and king salmon

**Method of Capture:** Fyke net, hoop net, minnow trap, seine

**Final Disposition:** ≤500 each of juvenile coho and king salmon (per approved drainage) may be collected, measured (weight and length), and released alive at the site of capture.  
≤200 each of juvenile coho and king salmon (per approved drainage) measuring 50 mm in length or larger may be anesthetized (**Stipulation #7**) for stomach contents removal (via gastric lavage) and scale collection before live release.  
≤2 individuals of each unknown species may be killed and saved for later identification.  
All unintended mortalities must be recorded and returned to capture site waters.

---

**COLLECTION REPORT DUE January 31, 2016** and **RESEARCH REPORT DUE June 30, 2016**; see **Stipulations #2** and **#3** for more information. Data from such reports are considered public information. Reports must be submitted to the Alaska Department of Fish and Game, Division of Sport Fish-HQ, 333 Raspberry Rd, Anchorage, AK 99518, attention: Scott Ayers (267-2517; [dfg.dsfp.permitcoordinator@alaska.gov](mailto:dfg.dsfp.permitcoordinator@alaska.gov)). A report is required whether or not collecting activities were undertaken.

**GENERAL CONDITIONS, EXCEPTIONS, AND RESTRICTIONS**

1. This permit must be carried by person(s) specified during approved activities who shall show it on request to persons authorized to enforce Alaska's fish and game laws. This permit is nontransferable and will be revoked or renewal denied by the Commissioner of Fish and Game if the permittee violates any of its conditions, exceptions, or restrictions. No redelegation of authority may be allowed under this permit unless specifically noted.
2. No specimens taken under authority hereof may be sold, bartered, or consumed. All specimens must be deposited in a public museum or a public scientific or educational institution unless otherwise stated herein. Subpermittees shall not retain possession of live animals or other specimens.
3. The permittee shall keep records of all activities conducted under authority of this permit, available for inspection at all reasonable hours upon request of any authorized state enforcement officer.
4. Permits will not be renewed until detailed reports, as specified in the Stipulations section, have been received by the department.
5. UNLESS SPECIFICALLY STATED HEREIN, this permit does not authorize the exportation of specimens or the taking of specimens outside of existing regulations.

  
\_\_\_\_\_  
Fish Resource Permit Coordinator  
Division of Sport Fish

  
\_\_\_\_\_  
Sheila A. Cameron for  
Director  
Division of Sport Fish

  
\_\_\_\_\_  
18 MAY 2015

Date

## Appendix B. 2016 Fish Resource Permit



STATE OF ALASKA  
DEPARTMENT OF FISH AND GAME  
333 Raspberry Road  
ANCHORAGE, ALASKA 99518

Permit No. **SF2016-158**

Expires: **12/31/2016**

**FISH RESOURCE PERMIT**  
(For Scientific/Collection Purposes)

**This permit authorizes:**

**Benjamin Meyer**

(whose signature is required on page 3 for permit validation)

Of

**University of Alaska**  
**902 Koyukuk Drive, Room 207, Fairbanks, AK 99775**  
**(907) 232-0280      bemeyer@alaska.edu**

to conduct the following activities from **May 5, 2016** to **December 31, 2016** in accordance with AS 16.05.930 and AS 16.05.340(b).

**Purpose:** To assess the impacts of climate change on juvenile coho and king salmon growth potential from Kenai River tributaries of differing hydrologic settings.

**Location:** Beaver Creek (244-30-10010-2025), Ptarmigan Creek (244-30-10010-2231), and Russian River (244-30-10010-2158), and the mainstem of the Kenai River (244-30-10010) in the vicinity of these tributaries.

**Species:** Chinook salmon and coho salmon

**Method of Capture:** Fyke net, hoop net, minnow trap, seine

**Final Disposition:** ≤6,000 each of juvenile Chinook and coho salmon may be collected, measured (weight and length), and released alive at the site of capture.

≤880 each of juvenile Chinook and coho salmon measuring 50 mm in length or larger may be anesthetized (**Stipulation #7**) for stomach contents removal (via gastric lavage) and scale collection before live release.

≤2 individuals of each unknown species may be killed and saved for later identification.  
All unintended mortalities must be recorded and returned to capture site waters.

**COLLECTION REPORT DUE January 31, 2017** and **RESEARCH REPORT DUE June 30, 2017**; see **Stipulations #2** and **#3** for more information. Data from such reports are considered public information. Reports must be submitted by email ([dfg.dsfcpermitcoordinator@alaska.gov](mailto:dfg.dsfcpermitcoordinator@alaska.gov)) or by mail to: Alaska Department of Fish and Game, Division of Sport Fish-HQ, 333 Raspberry Rd, Anchorage, AK 99518. A report is required whether or not collecting activities were undertaken.

**GENERAL CONDITIONS, EXCEPTIONS, AND RESTRICTIONS**

1. This permit must be carried by person(s) specified during approved activities who shall show it on request to persons authorized to enforce Alaska's fish and game laws. This permit is nontransferable and will be revoked or renewal denied by the Commissioner of Fish and Game if the permittee violates any of its conditions, exceptions, or restrictions. No redelegation of authority may be allowed under this permit unless specifically noted.
2. No specimens taken under authority hereof may be sold, bartered, or consumed. All specimens must be deposited in a public museum or a public scientific or educational institution unless otherwise stated herein. Subpermittees shall not retain possession of live animals or other specimens.
3. The permittee shall keep records of all activities conducted under authority of this permit, available for inspection at all reasonable hours upon request of any authorized state enforcement officer.
4. Permits will not be renewed until detailed reports, as specified in the Stipulations section, have been received by the department.
5. UNLESS SPECIFICALLY STATED HEREIN, this permit does not authorize the exportation of specimens or the taking of specimens outside of existing regulations.

Permit Coordinator  
Division of Sport Fish

*Sheila A. Cameron for*

Director  
Division of Sport Fish

*May 5, 2016*

Date

## Appendix C. IACUC Approval Form



(907) 474-7800  
(907) 474-5993 fax  
[uaf-iacuc@alaska.edu](mailto:uaf-iacuc@alaska.edu)  
[www.uaf.edu/iacuc](http://www.uaf.edu/iacuc)

### Institutional Animal Care and Use Committee

909 N Koyukuk Dr. Suite 212, P.O. Box 757270, Fairbanks, Alaska 99775-7270

March 11, 2016

To: Mark Wipfli, Ph.D  
Principal Investigator  
From: University of Alaska Fairbanks IACUC  
Re: [720490-3] Alaska EPSCoR OIA-1208927: Effects of climate change on growth of juvenile Chinook and Coho Salmon in three sub-basins of the Kenai River

The IACUC has reviewed the Progress Report by Full Committee Review and the Protocol has been approved for an additional year.

Received: February 22, 2016  
Initial Approval Date: April 20, 2015  
Effective Date: March 10, 2016  
Expiration Date: April 20, 2017

This action is included on the March 10, 2016 IACUC Agenda.

#### **PI responsibilities:**

*Acquire and maintain all necessary permits and permissions prior to beginning work on this protocol. Failure to obtain or maintain valid permits is considered a violation of an IACUC protocol and could result in revocation of IACUC approval.*

*Ensure the protocol is up-to-date and submit modifications to the IACUC when necessary (see form 006 "Significant changes requiring IACUC review" in the IRBNet Forms and Templates)*

*Inform research personnel that only activities described in the approved IACUC protocol can be performed. Ensure personnel have been appropriately trained to perform their duties.*

*Be aware of status of other packages in IRBNet; this approval only applies to this package and the documents it contains; it does not imply approval for other revisions or renewals you may have submitted to the IACUC previously.*

*Ensure animal research personnel are aware of the reporting procedures detailed in the form 005 "Reporting Concerns".*