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A Social-Ecological Approach to Understanding the Structure, Function, and Challenges Faced by Fisheries

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A SOCIAL-ECOLOGICAL APPROACH TO UNDERSTANDING THE STRUCTURE,

FUNCTION, AND CHALLENGES FACED BY FISHERIES

by

Chase C. Lamborn

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ABSTRACT

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by

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Utah State University, 2022

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Fisheries throughout the world play important social and ecological roles, and they are also subject to many social and ecological pressures. The tension between roles and pressures is increasing; as a result, many fisheries are being utilized to, or over their capacity, which ultimately threatens their sustainability. To address these challenges, this dissertation provides insights and tools to help us better understand fisheries and the challenges they face. The first study explored the impacts of an earlier spring runoff in Montana. Earlier runoff has resulted in lower and warmer summer flows, which stress coldwater species like trout, affecting fishing quality. Managers, along with outfitters and guides, are altering fishing practices to reduce resource impacts. As runoff continues to shift, August, the once-coveted month offering high quality angling opportunities, will be fraught with unfavorable conditions and fishing restrictions. The second study presents an innovative method that improves the development of social-ecological models and increases the comparability of models across different social-ecological systems. I showed how this approach can illustrate the breadth and interconnectedness of a social-ecological system and explore a system's sustainability. Using a collaboratively developed model of the Kenai fishery, I identified how the nature of salmon (migratory) and their habitat (large and unpredictable) leads to uncertainty about effective management strategies. This uncertainty, in addition to a large and diverse set of resource users, creates conflicting management visions that ultimately paralyze a governance system operating under collective-choice rule. The third study evaluates how fire and post-fire flooding affect a fishery. Through stakeholder interviews and a model-guided literature review, I identified fish populations that are the most vulnerable to long-term fire-related impacts. Vulnerable populations are isolated, lack quality habitat alternatives, and have low abundance. Applying this to the Kenai, I concluded that early-run Chinook salmon are the most vulnerable to fire, and if impacted, early-run Chinook have the greatest potential to severely impact the broader fishery through a chain of negative interactions. Collectively, this dissertation provides insights and tools to help us better understand fisheries, the challenges they face, and social-ecological systems more broadly.

(250 pages)

PUBLIC ABSTRACT

A Social-Ecological Approach to Understanding the Structure, Function, and Challenges Faced by Fisheries

Chase C. Lamborn

Fisheries throughout the world play many important roles, and they are also subject to many pressures. The tension between roles and pressures is increasing, and as a result, many fisheries are being utilized to, or over their capacity, which ultimately threatens their sustainability. To address these challenges, this dissertation provides insights and tools to help us better understand fisheries and the challenges they face. The first study explores the impacts of an earlier spring runoff in Montana. Earlier runoff has resulted in lower and warmer summer flows, which is stressing coldwater species like trout. This stress is affecting fishing quality, and the state of Montana, along with outfitters and guides, are altering fishing practices to reduce resource impacts. As runoff trends continue, August, the once-coveted month offering high quality angling opportunities, will be fraught with unfavorable conditions and fishing restrictions. The second study presents an innovative method for developing social-ecological models. I show how this approach can illustrate the breadth and interconnectedness of a social-ecological system and explore the components and interactions affecting a system's sustainability. Using a collaboratively developed model of the Kenai fishery, I identified how the nature of salmon (migratory) and their habitat (large and unpredictable) leads to uncertainty about effective management strategies. This uncertainty, in addition to a large and diverse set of people using the fishery, creates conflicting management visions, which ultimately paralyze the governance system. The third study evaluates how fire and post-fire flooding can affect a fishery. Through stakeholder interviews and a literature review, I identified fish populations that are the most vulnerable to long-term fire-related impacts. Vulnerable populations are isolated, lack quality habitat alternatives, and have low abundance. Applying this to the Kenai, I concluded that early-run Chinook salmon are the most vulnerable to fire, and if impacted, early-run Chinook have the greatest potential to severely impact the broader fishery through a chain of negative interactions. Collectively, this dissertation provides insights and tools to help us better understand fisheries and the challenges they face.

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Chase C. Lamborn

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CHAPTER I

INTRODUCTION

Fisheries around the world are influenced by many different social and ecological pressures. A single fishery can fill multiple roles, acting as a commercial, recreational, and subsistence fishery all at the same time. In addition, fisheries are subject to acute disturbance events and gradual exogenous stressors like climate change. The tension between these pressures is increasing due to growing demand for both food and recreational experiences. As a result, many fisheries are being utilized to, or over their capacity (FAO, 2020; Pauly and Zeller, 2017).

The sustainability of a fishery has both social and ecological dimensions. Well-functioning fisheries provide food, contribute to local, regional, and global economies, and add to societal well-being. However, poor-functioning fisheries can create a host of social (Martin, 2008; Trimble and Johnson, 2013) and ecological (Worm et al., 2006) problems. As the pressures on fisheries increase around the world, there is an urgent need to develop innovative approaches to help us better understand these social-ecological systems and the challenges they face. The goal of this research is to develop methods and frameworks that can be used to organize and understand complex systems facing complex problems. Specifically, this research provides tools to help us understand fisheries and the many endogenous and exogenous pressures exerted on them that may affect their long-term sustainability.

1. Background

1.1 A fishery

A fishery, put simply, is an area where fish are caught. This one defining attribute incorporates a wide spectrum of *fisheries* that range from commercial, to recreational, to subsistence, and every combination of the three. Fisheries in the Intermountain West region of the US are largely classified as recreational, with a small element of subsistence. Coastal salmon fisheries in Alaska support robust commercial, recreational, and subsistence activities, but to varying degrees depending on the fishery being examined.

1.2 State of fisheries

The condition of fisheries throughout the world is varied—some are doing quite well while others are not. Regardless of their state, each fishery faces unique challenges ranging in severity and scale. For example, marine fisheries throughout the world are increasingly being fished at unsustainable levels. The rate of unsustainable harvest has increased from 10 percent in 1974 to 34.2 percent in 2017 (FAO, 2020). Inland recreational fisheries can also face overharvest issues (e.g., Embke, 2019). Harvest sustainability is a very important indicator; however, it does not convey the vastly different social and ecological pressures that may lead to undesirable outcomes. Therefore, in addition to harvest sustainability, it is also important to look at a host of variables and their interactions to evaluate a fisheries state and sustainability.

1.3 Defining sustainability

The term sustainability is often used generally and does not receive the specificity needed to fully understand the goals implied by it. Harvest and biomass are two common indicators of sustainability. However, these are only two of the many measures which can be used to define sustainability (Charles, 2001). There may be differences in how sustainability is defined among the people using the resource, and between the people using the resource and the system governing it. Therefore, it is important to identify the differing perspectives of 'sustainability' when exploring complex social-ecological systems.

1.4 Organizing complexity

Fisheries vary in their complexity. Some have few social and ecological components and interactions, such as a community fishing pond, and others have many components and interactions, like a coastal salmon fishery. Regardless of their scale and complexity, fisheries and other natural resource systems have a foundational structure that is comprised of a resource system, resource units, users, and a governance system (Ostrom, 2007; 2009). Pressures can be placed from within (endogenous) or from outside (exogenous) a fishery. Frameworks such as Ostrom's (2009) are helpful tools to organize the complexity present in natural resource systems like fisheries. Once there is an understanding of the structure and function of a fishery, the outcomes of endogenous and exogenous pressures can be better understood.

2. Research objectives

Fisheries are incredibly diverse and affected by a host of endogenous and exogenous variables that can affect their sustainability. The goal of this research is to develop methods and frameworks to organize and understand complex systems facing complex problems. Specifically, this research has taken a social-ecological approach to expand our understanding of fisheries and the challenges they face.

This dissertation has two objectives, which are: 1) Develop a method for systematically mapping the social and ecological components and interactions of a fishery; and 2) Expand our understanding about how environmental change and disturbance can impact the social and ecological components of a fishery.

3. Overview of dissertation

This dissertation consists of three manuscripts (Chapters II, III, and IV). Chapter II has already been published in *Fisheries Research* (Lamborn & Smith, 2019). Chapters three and four will be submitted for publication shortly. Each manuscript explores fisheries through the lens of social-ecological research to expand our understanding of fisheries and the challenges they face. The fifth chapter provides a brief discussion of the findings, contributions, limitations, and future direction for this line of research.

Chapter II expands the discussion of shifting runoff cycles in the western United States. This was done by interviewing fishing outfitters and guides, government researchers, and state fisheries biologists/managers working within the Yellowstone River watershed (Montana, USA) to understand the social and ecological impacts of shifting runoff. I identified common themes in the interview data pertaining to how the broad spectrum of interviewees perceive the shift in runoff, how they are affected by it, and what strategies they employ to address these issues.

Chapter III uses an innovative Fuzzy Cognitive Mapping (Kosko, 1986) method grounded in Ostrom's (2009) social-ecological framework to collaboratively build a comprehensive social-ecological model of Alaska's Kenai fishery. The results present the structure and function of the fishery. I then use this model to identify factors contributing to sustainability issues faced throughout the Kenai.

Chapter IV uses the social-ecological model developed in Chapter III to explore how fire affects the social and ecological components of a salmon fishery. I used this model as an interview guide where stakeholders identified and described how fire has affected the Kenai fishery. In addition, I use this model as an organizational tool to guide a literature review focused on how fire impacts a fishery. Lastly, I use the information gathered in the interviews and literature review to identify how the Kenai fishery could suffer long-term fire-related impacts.

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CHAPTER II

HUMAN PRECECEPTIONS OF, AND ADAPTATIONS TO, SHIFTING RUNOFF CYCLES: A CASE STUDY OF THE YELLOWSTONE RIVER (MONTANA, USA)

Abstract

Throughout the western United States, researchers have started documenting a trend toward earlier runoff, lower in-stream flows, and warmer-than-average water temperatures. These ‘drought-like’ stream conditions often lead to negative ecological, economic, and social consequences. To gain a deeper understanding of these impacts, we focused our investigation on the Yellowstone River, which experienced a major drought event in 2016. This drought lead to an outbreak of Proliferative Kidney Disease that killed approximately 10,000 fish and resulted in an emergency closure of 183 miles of the river for 15 days. We conducted semi-structured, in-depth interviews with outfitters, guides, researchers, and fisheries biologists working within the Yellowstone River Watershed. Our work was guided by three objectives: 1) determine if people perceive changes in the runoff cycle; 2) identify the impacts of changing runoff; and 3) if impacts are occurring, document what adaptations strategies are being used to address them. In our discussions, respondents described an earlier runoff, shorter and more intense runoff, and more interannual variability in runoff. The impacts respondents associated with these changes were: 1) increased uncertainty in yearly planning and fishing quality; 2) altered fishing quality; 3) changes in species distributions; 4) disease outbreak; and 5) imposed fishing restrictions. Respondents also described the following adaptations to manage the

impacts: 1) altering catch-and-release practices; 2) temporally shifting trips; 3) spatially shifting trips; 4) drought anticipation; and 5) targeting warm water species.

1. Introduction

Hydrologic and thermal regimes are fundamentally important for aquatic ecosystems. The characteristics of a stream's hydrology is critical for the species that live within the system given its effects on water quality, energy flows, habitat, and biological interactions (Karr, 1991; Poff et al., 1997; Poff and Ward, 1989). In addition, stream temperature is vitally important for physiological processes of aquatic species (Pörtner and Farrell, 2008; Pörtner et al., 2008; Takasuka et al., 2007), fish growth (Neuheimer and Taggart, 2007), abundance (Sloat and Osterback, 2012, Ebersole et al., 2003), and distribution (Buisson et al., 2008). In short, changes to hydrology and temperature can have dramatic impacts to aquatic systems.

Throughout the western U.S., researchers have documented recent trends in stream runoff and temperature. These trends include earlier runoff, lower summer flows, and warmer water temperatures (Al-Chokhachy et al., 2017; Leppi et al., 2012; Isaak et al., 2012; Rood et al., 2005; Stewart, 2005; 2004), and some research has even identified an acceleration in these trends over the last 8 to 10 years (Leppi et al., 2012). The main driver of these changes is increased air temperature (Leppi et al., 2012; Isaak et al., 2012), with recent air temperatures being especially warmer-than-average during the winter and spring seasons (Lettenmaier et al., 1994; Dettinger and Cayan, 1995). With air temperatures expected to increase (IPCC, 2014), models predict large decreases in fresh, coldwater habitat, ultimately leading to decreases in coldwater species distribution and abundance (Jones et al., 2013; Wenger et al., 2011; Lessard and Hayes, 2003).

While recent research has documented trends toward lower-than-normal in-stream flows and warmer-than-average temperatures across the western U.S., researchers have only been able to speculate about how these changes will affect the diverse social and ecological components of a river system; most have just focused on the ecological components of a river system, such as fish (Al-Chokhachy et al., 2017; Isaak et al., 2012). These studies have provided valuable insights into how stream discharge, as well as stream temperatures, are changing. Given the consistent evidence presented in this line of work, social scientists can now begin to examine how changes in runoff affect the social components of river systems as well.

Only a few investigations have documented how changes in hydrologic and thermal regimes will impact both ecological *and* social systems. Jones et. Al. (2013) modeled the potential biological and economic impacts of climate change on freshwater fisheries in the U.S. using different climate scenarios. The authors first modeled the biological impacts of climate change by mapping the current habitat for three thermal guilds. Under current greenhouse gas emissions, their model projected a 50% reduction in coldwater habitat by 2100. Lost coldwater habitat would result in coldwater species being replaced by fish species in the warm- and rough-water guilds. The authors also modeled the economic impacts of this habitat shift, estimating a national economic loss of between $81 million and $6.4 billion by 2100, depending on the greenhouse gas emission scenario. Similarly, Ficke et al. (2007) outlined the many ways climate change can affect freshwater fisheries and the people that rely on them. They describe how climate change can impact water (i.e., increasing water temperatures, decreasing dissolved oxygen, increasing toxicity and pollutants, shifting hydrologic regimes, increasing hydrologic variability, etc.), how these changes will impact fish, and how impacts to fish will ultimately affect food availability and economies that rely on recreational and/or commercial fishing.

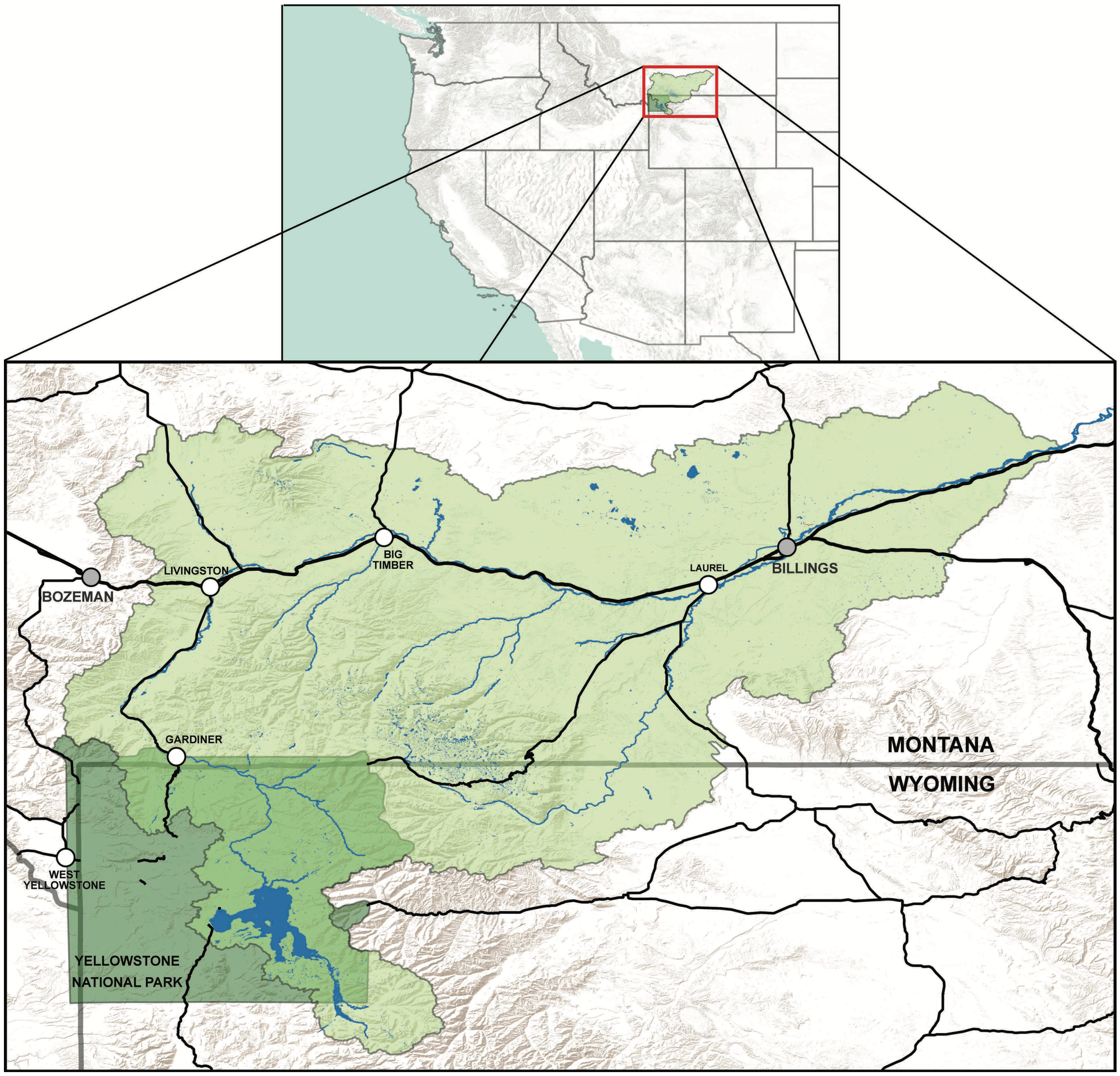
Given the scant amount of research investigating the social implications of altered hydrologic and thermal regimes—specifically the impacts to fish, fishing, and tourism—our investigation set out to document the implications for one specific river—the Yellowstone River in Montana, USA. Our work was guided by three objectives: 1) determine if people perceive changes in the runoff cycle; 2) identify the impacts of changing runoff; and 3) if impacts are occurring, document what adaptations strategies are being used to address them.

2. Study Area

The Yellowstone River is an ideal study area for four reasons. First, it is a well-known fishery that attracts many anglers and is home to many outfitters and guides (O&Gs). A larger population of O&Gs increase the likelihood of obtaining a more diverse set of perceptions and behaviors. Second, the Yellowstone River is a long, free-flowing river that traverses a wide geographic and temperature range. This made it a good candidate for investigating the effects of river flow and temperature on changes in fish populations, the behavior of anglers, and the local fishing industry. The river stretches from Yellowstone Lake down to Billings, Montana, covering 247 miles (Figure 1). Third, the Yellowstone River has experienced multiple low-flow and warm-water events in the recent past (i.e., 2013, 2015, and 2016) (USGS Livingston, MT gauge station). The worst of these events occurred in 2016, when the Yellowstone River experienced a severe low- and warm-flow event and an outbreak of Proliferative Kidney Disease (PKD), which is caused by a parasite—*Tetracapsuloides bryosalmonea*—that affects fish's organs. After approximately 4,000 fish were found dead, the Montana Department of Fish, Wildlife, and Parks closed a 183 mile stretch of the Yellowstone to all recreational use—from Yellowstone National Park to Laurel, Montana (Opitz and Rhoten, 2017). Up to 10,000 Mountain Whitefish (*Prosopium williamsoni*) were estimated to have been killed by the disease during the outbreak in 2016 (Byron, 2016). The fourth and final reason the Yellowstone River is an ideal location to investigate changes in fish populations, the behavior of anglers, and the impacts on local fishing industry is the opportunity to integrate documented shifts in temperature and runoff within the river (Al-Chokhachy et al., 2017) with data we gathered from our interviews.

Figure 2.1.

Yellowstone River Watershed



3. Methods

To gain an in-depth understanding of how people who rely on the Yellowstone River are perceiving, being affected by, and reacting to the documented environmental change within the Yellowstone River watershed, we conducted semi-structured interviews with outfitters, guides, fisheries biologists, and researchers. Data generated through the interviews were analyzed using an inductive coding and thematic analysis approach (Corbin and Strauss, 2007). An inductive approach allowed us to freely explore the complex and evolving relationships between the economic, environmental, and social factors of the Yellowstone River. Our analysis blended qualitative (i.e., responses from interviewees) and quantitative research (i.e., outside, peer-reviewed data). We attempted to tie the inferences we gained from the interviews back to published research, ultimately tying together lived experiences with documented ecological processes and changes.

We started by interviewing outfitters, guides, fisheries biologists, and researchers because they are likely to: 1) have an intimate knowledge of the Yellowstone River; 2) be sensitive to both ecological and social changes that affect the river; and 3) have knowledge of, and can be economically affected by, ecological events and management decisions (e.g., the river closure in response to the PKD outbreak in 2016). An internet search provided a list of O&Gs who operate on the Yellowstone River while the Montana Fish, Wildlife and Parks website listed local fisheries biologists. From these initial contact lists, snowball sampling was used to identify additional O&Gs, biologists, and others who had worked on, or studied, the river. While all of our respondents provided additional people for us to contact, we only contacted those references that fit within the scope of our study, meaning they had detailed knowledge of, and frequent interaction with, the ecological processes of the Yellowstone River.

An interview guide of open-ended questions was used to direct conversations. The interviews were structured around three sets of questions related to: 1) perceptions of hydrologic and thermal shifts on the Yellowstone River; 2) noticeable impacts of perceived shifts; and 3) adaptive responses that have, or are, being taken to address these impacts. To avoid response bias, all conversations were focused specifically on stream runoff/temperature and *drought events*—which we defined as extreme low- and warm-flow events—and we never mentioned the terms “climate change” or “global warming” during the interviews. However, most interviewees brought up climate change, and discussions about climate change generally proceeded from that point.

A total of 12 interviews were completed. Only one person we contacted did not agree to participate because they did not feel they had enough experience to inform our study. Data collection ceased when interviewees provided no new contacts. Given the high density of O&Gs working along the Yellowstone River, and the lack of new suggestions for potential interviewees, we are confident that we reached the majority of potential participants that fit within the scope of our target population. While the overall number of participants may seem low, we are also confident in the breadth and depth of our data because new interviewees did not yield additional information, indicating we had reached theoretical saturation (Corbin and Strauss, 2007).

Interviews were conducted over the phone, recorded with the permission of the respondent, transcribed verbatim, and uploaded into the software Nvivo, which was used for all data analysis. The interviews ranged from 44 to 128 minutes in length, with an average duration of 71 minutes. Because the focus of this study was long-term trends, we were particularly interested in interviewing individuals who had the greatest amount of experience with the Yellowstone River. Years of experience, which is the number of years a respondent had directly worked on the Yellowstone River, ranged from 7 to 57 years, with a mean of 21 years. Fisheries biologists and researchers tended to have the fewest years of direct contact with the river, and O&Gs had the most.

Our analysis of the interview data followed a phenomenological approach given our focus was on a group of individuals who have a common lived experience with a phenomenon (i.e., changes in hydrological regimens and low- and warm-flow events) (Creswell, 2013). Phenomenological studies utilize varied sources of data to describe the phenomenon and its ramifications (Moustakas, 1994; Creswell, 2013), which we were able to by connecting our interview data to published, peer-reviewed literature (e.g. Al-Chokhachy et al., 2017). This approach enabled us to accomplish three things: 1) corroborate lived experiences with scientifically documented phenomena, 2) describe scientifically documented phenomena through the lens of people's lived experiences, and 3) expand our knowledge of the impacts of shifting stream temperature and hydrology.

Following the data analysis process outlined by Corbin and Strauss (2007), data were first coded into high-level categories. This was done by grouping data into general descriptive categories, such as "runoff," "water temperatures," "fish," "adaptations," etc. Once all the data were categorized, we returned to each high-level category and searched for additional nuance and structure within the data to create subthemes. For example, within the high-level "fish" category, subthemes were "whitefish," "smallmouth bass," "cutthroat," "distribution," "changes," etc. Once all data were organized into higher- and lower-level categories/themes, we iteratively reviewed the data, testing and refining concepts, identifying connections between themes through axial coding, writing memos, and building themes into narratives.

4. Results

Table 2.1.

Higher- and Lower-level Categories/Themes Generated from the Analysis

Higher-level category/theme		Lower-level category/theme
Observed changes in hydrology		Earlier runoff
		Shorter and more intense runoff
		Increased annual variability
Impacts		
	Uncertainty	Uncertainty in booking guided trips
		Warmer water in late-summer
	Altered fishing conditions	Tougher fishing conditions
		Increased fishing pressure
		Changes in aquatic insect life
	Changes in species distributions	Decreased range of Cutthroat Trout
		Increased range of Smallmouth Bass
	Disease outbreaks	Whitefish die-off
		Limited geographic scope
		Large social and economic impacts
	Imposed fishing regulations	Hoot-owl regulations
		2016 full river closure
Adaptations		
		Altering catch-and-release practices
		Temporal shifts
		Spatial shifts
		Drought anticipation
		Targeting warm-water species

The final set of higher- and lower-level categories/themes generated from the interview data are presented in Table 1. We first describe how respondents perceived hydrologic and thermal shifts on the Yellowstone River. We then discuss the impacts of these shifts. Finally, we present the adaptation strategies used to address these challenges.

4.1. Observed Changes in Hydrology

During our interviews, we asked respondents if they had noticed any changes in the runoff cycle over the time they have spent on the river. Only a few indicated there have been no long-term changes, that runoff is just "cyclical." One challenge with being able to perceive a long-term trend is the highly variable nature of the runoff cycle, and without critically analyzing runoff data, or having a long timeframe to refer to, seeing long-term changes can be very difficult. One respondent illustrated this by saying,

> These things are slow enough that they are hard to perceive… I have been so intensely focused on [my business] from day to day that I haven't really noticed a big difference. Though again, if you talk to people who have been here for 50 years they will say that winters used to be so much worse and start sooner and end later. So I do believe that it is happening in the long-term. But again, there is so much variation that it is hard to perceive those long-term trends.

Most of the O&Gs had perceived, or were at least aware of long-term changes in the runoff cycle. The three main changes they identified were: 1) *earlier runoff*; 2) *shorter and more intense runoff*; and 3) *increased annual variability* (i.e., drought and flood years). One outfitter who was not very experienced on the Yellowstone River relative to the other O&Gs we interviewed, noted: "Thirteen years of experience makes the longer-term trends harder to spot, but certainly I have read that runoff is tending to start earlier and end earlier, and that would fit with my limited experience." Another outfitter who had many years of experience working on the Yellowstone River said,

> When I first went to work for the fly shop here, the story I used to tell is just so much different than what I see now…I would say that somewhere around the 4th of July is when the Yellowstone would usually start to be clear enough…that we could start fishing…Now we have seen a lot of years where that early July clearing is more like the 25th of June.

Historically, fishing before July 4th was almost unheard of, as one outfitter said, "You can talk to the old-timers and they say, 'Yeah, we never used to fish the Yellowstone before the Fourth of July.'" However, in recent years, fishing before July 4th is not uncommon, unless there is a big snow year.

Respondents not only described the runoff cycle shifting to earlier in the year, they also described how the overall cycle has become *shorter and more intense*. For example, one outfitter said,

> I think [runoff] has gotten a lot shorter, and at times it can be a lot more intense actually. It seems like the intensity is a shorter lifespan…It gets really high for a very short period of time and drops back down or moderates… It seems to be starting sooner and not lasting as long. Unless we have a really big snowpack.

Beyond shifting runoff cycles, some respondents also said river conditions have become *more variable from year to year*. One outfitter illustrated this by saying,

> You know, going on the notion that weather is just getting more extreme in both directions. The general trend will be toward earlier fishing, but we will also have some really nasty winters, and possibly some years where runoffs last longer than usual…there are anomalies, like 2011… [we] weren't able to get on the river until almost the beginning of August because of a very heavy snow year.

Speaking of long-term changes in variability, and using the year 1988, the year of the large wildfire in Yellowstone National Park as a reference, one outfitter said,

> I think we have had more years with less snowpack since …before 1988. We certainly had light years before and heavier years before, don't get me wrong on that, [but] I have seen more extremely high crests [in runoff] since 1988 than I have experienced in my [30 years of] experience prior to 1988...

This outfitter has observed two changes, which are, on average, less snowpack and more extremely high crests in runoff. They also attributed a portion of these changes to the change in forest canopy since the large fire.

Overall, only a few O&Gs did not perceive long-term changes in the Yellowstone River's runoff cycle, and called any variation "cyclical"; however, most O&Gs did perceive, or were aware of long-term changes, which were specifically an earlier runoff cycle, changes in runoff distribution, and annual increased variability. But even those participants who did not perceive long-term trends in runoff later described the impacts they have felt from recent low-flow events, and the adaptation strategies they have used to manage the impacts. Therefore, even though participants may not have perceived recent events as long-term trends, they were still reacting to the associated impacts of recent shifts in runoff.

4.2. Impacts from Shifting Hydrology on the Yellowstone River

4.2.1. Uncertainty.

As the runoff cycle shifts earlier in the season, less water becomes available during the hottest part of the summer. The combination of low water volume and high air temperatures result in high water temperature (Issak et al., 2012). The Yellowstone River has experienced some recent warm water years in 2013, 2015, and 2016 (USGS Livingston, MT gauge station). The summer of 2016 was especially severe, leading Montana Fish, Wildlife, and Parks to implement restricted fishing hours. These restricted hours, termed *Hoot-owl* restrictions*,* prohibit fishing from 2:00pm to Midnight. They are implemented when water temperatures reach or exceed 73° Fahrenheit (22.7° Celsius) for three consecutive days. The PKD outbreak occurred in August of that year, leading to the complete closure of the river.

There has always been an aspect of uncertainty regarding river and fishing conditions in the outfitting and guiding industry; however, O&Gs expressed that the increased variability of runoff magnitude and timing have created additional *uncertainty with regards to booking fishing trips*. During a drought year, low and warm river conditions in August can result in poor fishing conditions and possibly fishing restrictions. If there are multiple drought years in a row, followed by a flood year, O&Gs need to get the word out to potential clients to change their expectations about when fishing conditions are best. For example, one outfitter said,

> This year we actually had pretty good water flows and temperatures, but because of the troubles we have had in the previous couple years, people are a little gun-shy about making long-term plans for August on the Yellowstone.

Earlier runoff creates a high probability for low and warm water, which creates poor fishing conditions in August, and the possibly of river restrictions or closures. Increased variability from year to year also creates booking challenges, and great efforts are made by O&Gs to inform potential clients of each year's conditions so clients plan their summer fishing trips accordingly. O&Gs described the need to be cautious booking trips in August during these years because low and warm water conditions may impact the quality of fishing. One respondent said: "the past couple of years August has been tough for us, particularly for the fish because we have had low warm water."

4.2.2. Altered fishing conditions.

The impacts from low and warm flows usually occur in August. As water temperatures approach or exceed 70° Fahrenheit (21° Celsius), many O&Gs said *fishing slowed way down*. Speaking about how water temperatures affect fishing, one outfitter said, "the fishing does suffer. The fish are just not as eager to eat when they are getting into a stressful level of water temperatures." Another outfitter repeated, "the real hot summers and dry water years... That makes the fishing challenging if I was to say one thing. I mean tough fishing conditions." In addition to the tougher fishing conditions that come with low and warm water conditions, O&G expressed two other factors that have made fishing more challenging in recent years, which were *increased fishing pressure* and *changes in aquatic insect life*.

Increased fishing pressure was often cited as a long-term issue that has made fishing more difficult. Overall, more recreationists on the water, both anglers and non-anglers, with more artificial flies and lures in the water, and more fish being caught has dramatically changed the experience of fishing on the Yellowstone.

To be clear, many people said the Yellowstone is a great fishery, and they still have very good fishing days, but those days seem fewer and farther apart. It was also said that to have a good day, a person needs to be a much better angler now than in the past. When reflecting on how fishing has changed on the Yellowstone, one outfitter said,

> I will say that when I first moved here, it was very uncrowded, and to catch fish, man, you could put on any big fluffy dry fly you wanted and float down the river and cast at either bank, or wherever you wanted to cast, and it was going to work. You were going to catch fish doing it. Now, with the pressure that is out there, you do have to be a better angler.

Another outfitter touched on both increased use and changes in insect life as being reasons why fishing has become more difficult on the Yellowstone.

> I think [increased use] has made the fish tougher to catch. More pressure upon them, more flies on the water constantly floating by them, they are a lot more educated. It's hard to say for a fish that has a brain the size of a pea to be educated, but they are harder to catch. Their feeding habits have changed a little bit. It used to be that just fishing a dry fly all day, start to finish, you could do well. If you knew where and how to fish the dry fly, you would be catching trout all day, and now it's not always the case. The only thing I can think of is that it is due to, some of it may be biological. I do think that the hatches might be a little bit less, or shorter, than they seemed to be in the past, but a lot of it could be due to the pressure too. So, yeah, the fishing has changed.

Many O&Gs said hatches—the time when aquatic insects transition from their nymph phase to their terrestrial phase—have changed over the years, which has made fishing more difficult. When asking an outfitter if the changes he had seen in the runoff cycle have affected the fish and the quality of fishing, he responded by saying,

> I have seen more of an impact on our insect life. It is just drastically different from what it was when I moved [to the Yellowstone]. I would say there are definitely less bugs and it definitely seems to change. Dry fly fishing is not as reliable as it used to be…. In the springtime when we used to have good insect hatches, Bates, March Browns, Mother's Day Caddis, all those hatches barely happen anymore…I wouldn't say they are gone, but they don't happen in the numbers that they used to.

After hearing that aquatic insect life has changed from multiple O&Gs, we asked managers if they were aware of these changes and if they had any data to support what the O&Gs were describing. One manager described how hatches have changed, and how the dry fly fishing has suffered because of it. He also described how the condition factor—a metric that uses a fish's length and weight to quantify their health—has not changed, which indicates that the fish are getting enough food. Therefore, these changes seem to be affecting the quality of fishing more than the health of the fish themselves.

We asked another biologist if he had, or was aware of, any data that could illuminate what is going on with the Yellowstone's aquatic insects, and he said:

> We don't…Visually, and I'm guessing that you have probably heard this from some of the O&Gs, hatches and things have certainly changed through time. Most of what I hear is in terms of abundance, and I would tend to agree. Timing seems to be off a little bit with some of those, too. Mother's Day Caddis is not on Mother's Day anymore, and we think that's because of the change in flow regimes. A lot of times, Mother's Day can be a pretty good runoff, and 20 years ago the runoff around Mother's Day was just getting started. We've had those kinds of shifts.

When discussing all of these impacts, and how things have changed over time, many outfitters explained that yes, things have changed, and those changes do have an impact and are concerning, but the fishing on the Yellowstone River is still good.

However, there was a strong consensus that fishing on the Yellowstone has changed and become more difficult, due to three predominant factors. The first factor, and probably the most temporary in duration, is low and warm water conditions that are becoming more frequent in August. Secondly, the Yellowstone River is receiving much more use now than it did in the past. Lastly, the aquatic insect life has changed on the Yellowstone River, which has seemed to make all fishing, but specifically the dry fly fishing, more difficult. O&G also describe how these three factors compound on each other and make fishing more difficult. For example, one outfitter said,

> Well, two things happen… [1)] the fish are less active [in warm water]; we catch fewer fish per unit time… You also get into situations where there are low-clear waters, and you still have high sun, [which] means you have [2)] a lot of spooky fish that have already been caught… so they are just plain less likely to bite…

4.2.3. Changing species distributions.

In addition to altered fishing conditions, respondents also described *changes in species distributions* that were associated with changes in runoff and warmer water. The two changes in species distribution identified by respondents were: 1) *decreased range of Yellowstone Cutthroat Trout* (*Oncorhynchus 24larkia bouvieri*) and 2) *increased range of Smallmouth Bass* (*Micropterus dolomieu*). On the upper Yellowstone, the Yellowstone Cutthroat Trout is the only native sport fish. However, there are introduced, non-native species that are critically important sport fish as well, such as the Rainbow (*Oncorhynchus mykiss*) and Brown Trout (*Salmo trutta*), both of which are coldwater sport fish. On the lower Yellowstone, where the water is warmer, there are non-native Smallmouth Bass (*Micropterus dolomieu*) that are also an important sport fish.

In the last 30 years, there has been a significant decline in Yellowstone Cutthroat. Describing how much the cutthroat population has declined, a fisheries biologist said that a section of river near Springdale, MT,

> [Historically] had around 200-250 cutthroat per mile, but by the time I got here and started my career, within the first 5 years we were lucky to catch 50 cutthroat total in that section, so pretty big drop in abundance there. Through time, if you go back and look at work that my predecessors did compared to what we are seeing now, there has been that gradual decline in cutthroat throughout the whole basin, but we see it in a much more significant rate in the lower end of the river.

Respondents attributed multiple factors to the decline of Yellowstone Cutthroat, including harvesting issues in the 1970s and 1980s (which were later resolved with catch-and-release ethics), competition between cutthroat and non-native gamefish like Rainbow and Brown Trout, increasing stream temperatures, and crossbreeding between cutthroat and Rainbow Trout. While crossbreeding might not first appear to be directly linked to changes in runoff, Rainbow Trout spawn on the ascending side of runoff and cutthroat spawn on the descending side (Muhlfeld et al. 2009), and changes in runoff have led to new overlaps in spawn timing. To further explain how this relates to a compressed runoff cycle, a biologist said,

> We've done research and know that in tributaries where [Rainbow Trout and Yellowstone Cutthroat Trout] spawn…they are using the same areas. Not only in the same tributaries, but they are in the same areas, so as we compress [the runoff cycle] we are increasing the risk of potential to see an increase in hybridization.

Smallmouth Bass are also increasing their range in the Yellowstone River; as one outfitter said, "[It] seems like there are more and more [Smallmouth Bass] every year. I caught more Smallmouth Bass in the sections I float this year than I ever have." The exact reason for their expansion is unknown, but a respondent who studies Smallmouth Bass in the Yellowstone River provided two of the leading hypotheses, which are: 1) warmer than average water temperatures are expanding their habitat; and 2) they have not yet reached the capacity of the environment in which they were introduced. This researcher continued by saying,

> There is growing evidence throughout the West that there is currently a lot of cool-water and warm-water fish that are expanding their ranges as stream temperatures warm, amongst other drivers. One of those cool-water fishes that has been making some pretty well documented expansions are Smallmouth Bass.

We asked a fisheries biologist if Smallmouth Bass were having an effect on the Yellowstone River's trout population, and he said,

> We haven't seen anything, especially up here. The report of abundance is so low on bass that there really hasn't been much of an effect here. As you move down river, there's quite a bit of overlap [between bass and trout], and as far as I know those guys aren't seeing any indication or trends at this point. They haven't seen an effect.

Among the O&G community, there are concerns about Smallmouth Bass impacting the trout fishery, as one outfitter said regarding the expanding range of Smallmouth Bass,

> [It is] a big concern…The state biologists are tracking them, and they have noticed an up-river trend in their abundance…I have heard from people back East and other areas where Smallmouth have taken over trout rivers, and they are known as voracious predators, and have had a big effect, at least anecdotally."

Even though there are concerns among O&Gs, managers did not seem highly concerned about Smallmouth Bass having a large impact on the trout fishery at this point. One respondent, when asked about the impact of Smallmouth Bass on trout in the Yellowstone, replied, "The majority of the [trout] population is rearing further upstream, bass aren't there yet… We don't have any data yet suggesting that they [should be a] major concern." While participants perceived the potential level of threat of Smallmouth Bass differently, *changing species distributions*, especially the decreasing range of Yellowstone Cutthroat Trout, remained a concern.

4.2.4. Disease outbreaks.

While its cause remains unclear, the outbreak of PKD in 2016 was a shocking event for those who witnessed it. One outfitter described floating down the river, emphasizing, "you literally [saw] dead fish pretty much all the time." Yet the long-term economic impacts of the PKD outbreak were minimized because the outbreak had the largest impact on Mountain Whitefish (*Prosopium williamsoni*), which are not a primary sport fish in the Yellowstone River. Respondents speculated that if PKD had infected and killed more trout, the social and economic impacts may have been much more severe and long-lasting. The year after the outbreak, O&Gs explained it was nearly back to "business as usual," though there were some changes in how people perceived the Yellowstone River, leading to decreased bookings in August 2017.

Determining the overall impact of the PKD outbreak is difficult; however, there are a few things that are known. The most apparent is that *the mortality caused by PKD overwhelmingly affected a very abundant population of whitefish.* As one biologist put it, "The number of whitefish [where the outbreak occurred] is really incredible. When you turn the electricity on [when electrofishing for our population estimates] your boat is surrounded by 20 to 50 whitefish all the time." When speaking with O&Gs about their 2017 fishing season—the year after the outbreak—they said they did not notice any changes in the whitefish population, and they still caught them regularly despite the previous outbreak.

The second thing we know is that fish mortality attributed to PKD was *confined to a fairly small geographic region*. The section of the Yellowstone River below the town of Emigrant, Montana, suffered the most severe impacts, with the highest mortality levels spanning a distance of only 8 river miles. Lastly, despite the abundance of whitefish and the limited geographic range of the outbreak, the management response to PKD was large and had a significant *social and economic impact*. For example, as one guide described impacts to the river translated to impacts in the community, stating, "[When] the entire river is closed like last year, some of the best restaurants in town were just dead. The hotels were dead." O&Gs that were unable to operate in areas outside of the closure suffered significant financial losses, given that summer is a short window in which they make the majority of the annual profit.

Because the outbreak occurred during a severe drought event, it would be easy to assume that drought conditions lead to PKD outbreaks; however, this is not necessarily the case. One respondent who studies PKD said, "Drought conditions alone don't cause the disease, but they can exacerbate the impacts of the disease." He explains,

> So far, every river we have collected healthy fish from in Montana, we have found evidence of the parasite. Now, we have a lot of rivers that in 2016 had comparable conditions as the Yellowstone, yet no one saw 10,000 dead fish. We have also documented now, through our archive samples, that the PKD parasite has been present in this system since at least 2011… The Big Hole, if you know it well, [experiences stressful conditions] every year with dewatering as a function of both weather/climate and irrigation. Every year it sees conditions that are likely much more stressful than what the Yellowstone saw in 2016… Yet, no giant fish kills.

As alluded to above, not only is PKD widespread in Montana, but it has also been there much longer than previously thought, leading researchers to hypothesize that the parasite that causes PKD is native to the Yellowstone River. However, without water samples dating back many years, researchers do not have the data to fully confirm it. With the parasite that causes PKD being widespread, and many rivers where it is present seeing regularly occurring drought conditions with no outbreak, predicting a future outbreak at this point is nearly impossible because the triggers for the outbreak are still not fully understood.

At the time of the outbreak, little was known about the parasite, leading Montana Fish, Wildlife and Parks to implement extreme management measures to reduce fish stress and contain the infection. Now knowing that many rivers in the region contain the parasite that causes PKD, and have for some time, managers would most likely respond much differently to a future outbreak. While it is difficult to fully quantify the impacts of the PKD outbreak, some are clear: the outbreak almost exclusively impacted an abundant population of whitefish that could withstand the losses, and it only affected a small geographic region. Perhaps what is most surprising is that the impacts of the closure had a greater social and economic impact than the outbreak itself. Yet while the river closure was an extreme measure, and would probably not be implemented again, all O&Gs in our study were supportive of the actions taken by Montana Fish, Wildlife, and Parks to protect the Yellowstone River, given the information they had at the time.

4.2.5. Imposed fishing regulations.

The full river closer in 2016 was a unique event; however, there are other regulations, such as Hoot-owl regulations, that are implemented to reduce the stress placed on fish during warmer-than-average water temperatures. Hoot-owl regulations are more commonly implemented, and O&Gs described being able to work around them and maintain business. However, when discussing the PKD outbreak with O&Gs, many discussed the impacts to their businesses and the area's economy. One outfitter compared the difference between Hoot-owl regulations and the 2016 river closure by saying the following:

> The Hoot-owls aren't terrible because people are still out here. Everyone just quits early and they are still out at the hotels and everything like that. They are still going to dinner. I don't know if Hoot-owls hurt us that much. Probably a little bit because people hear that there is a Hoot-owl, and maybe they say 'let's not go to Montana next week.' But usually people plan months ahead of time, and they are going anyway. Where like if the entire river is closed like last year, some of the best restaurants in town were just dead. The hotels were dead. That was different.

While O&Gs were directly impacted by the river closure, the closure had differing impacts within communities. As mentioned in the above quote, businesses that could not move, such as restaurants and hotels, were "dead" because of the river closure and people not coming to the area. In addition to restaurants and hotels being impacted, so were other businesses, as one fly shop owner said,

> The raft companies for instance, their season was simply over. By the time the river got reopened at all, they had to turn their crews loose and simply shut down because they couldn't deal with an indeterminate timeframe, so they got hurt much more significantly than I did.

Fly shops were also impacted by the closure, and depending on how deep within the closure the fly shop was, the greater the impact. For example, one fly shop owner from the middle of the closure said,

> A leading indicator of traffic through the store that we use a lot is fishing license sales. On a general basis, [fishing license] sales for us are multiple thousands [of dollars] a week. When it goes from that to less than $100 when the river is closed, it lets you know how many people are not walking through the doors.

Those with the ability to move out of the closure and guide in other waters were better able to buffer their losses, though they still too felt the impacts of management actions.

During drought conditions on the Yellowstone River, management actions aimed at reducing resource stress can lead to stress on the region's tourism industry. Different management actions, such as Hoot-owl regulations versus river closures, created different community impacts. Communities have seemingly adapted well to Hoot-owl regulations because people are still visiting. O&Gs can start trips earlier in the day, and other businesses, such as restaurants and hotels, can still capture revenue from those still coming to the region to fish and recreate. However, management actions such as full river closures—which given the new information on the parasite that causes PKD is unlikely to happen again—have a much greater impact on business in the tourism industry.

4.3. Adaptation Strategies

Interviewees revealed five strategies that they often use to adapt to drought conditions, including: 1) *altering catch-and-release practices*; 2) *temporally shifting trips*; 3) *spatially shifting trips*; 4) *drought* anticipation; and 5) targeting *warm-water species*. No single adaptation strategy is perfect, and many O&Gs used a combination of strategies.

As noted above, O&Gs found that fishing becomes more difficult when water temperatures exceed the normal range for trout. In addition, fish that are caught in high water temperatures and then released have an increased probability of mortality (Bartholomew and Bohnsack 2005). Most O&Gs still fish during low and warm flows, but when doing so, many expressed great concern for the resource and the fish. For example, one outfitter said, “When the river gets low and warm… it is one of those things, that if you go float the river you are worried about every fish you catch…” O&Gs know that there is a certain amount of mortality associated with catch-and-release fishing, but they also know that increased water temperatures increases the likelihood of mortality:

> As you know, there is going to be a certain amount of mortality no matter what you do in any kind of conditions, but as the water temperature goes up then the likelihood of the fish dying probably increases and there is a greater percentage of mortality. We are trying to mitigate that as best as we can with proper practices and procedures.

To reduce stress on fish during drought conditions, respondents frequently described *altering their catch-and-release practices.* The strategies they mentioned were using stronger tippet (i.e., fishing line), reeling in fish quickly so they do not reach complete exhaustion, keeping them in the water, and releasing them quickly.

O&Gs also use other strategies to reduce their impacts during drought conditions. These strategies can be categorized into *temporal and spatial adaptation*. *Temporal adaptation* includes self-imposed Hoot-owl regulations, which is where an O&G changes their own guiding hours before the state of Montana makes it mandatory. This means a guide will take their client fishing from dawn to around 2 pm, skipping the hottest and most stressful part of the day for fish. One outfitter summarized the strategy simply, saying to "change the hours, you know, like shift the day so we are starting earlier."

There is also *spatial adaptation*, which is generally the process of fishing in cooler water. During low and warm flows, one outfitter said he tries to chase cooler water,

> [We will do] an early morning float and get off the river pretty early, and then go fish a small mountain stream in the afternoon. [I] just try to maximize places where we are going to be dealing with reasonable water temperatures in the high mountain streams as long as they don't get dewatered completely in a drought year... It is a good change of pace in the day and just another way you can work around water conditions if they get challenging on the other rivers…. Another local thing, again, [is] that we have the spring creeks coming in just above town… the main thing is to try to avoid [high water temperatures].

Drought anticipation is another temporal strategy that includes avoiding fishing during the hottest parts of the year, and trying to schedule trips when water conditions are going to be less stressful for fish. This could still mean booking trips for August, but checking the snowpack and waiting to see what conditions are going to be like before doing so. For example, when dealing with poor snowpack, one outfitter said, "I just tend not to push my August calendar, and when folks inquire about it I just usually tell them to hang on until we have some idea [of what conditions are going to be like]." This response is not only from O&Gs, as clients are also starting to avoid August given the poor conditions in previous years. For example, one outfitter said that lately "August isn't as popular with booking…and I have certainly seen that with my own clientele."

Another adaptation strategy is *targeting warm-water species*, such as Smallmouth Bass and/or Carp when temperatures get really high. During periods when temperatures are too high for quality trout fishing, and there is a high probability that released trout will die, O&Gs instead target warm-water species. One outfitter said that there are a "handful" of guides that have started to take advantage of these opportunities:

> In the last few years there have been a handful of guides in the Bozeman area that every time they can talk someone into going carp fishing they do that instead of going trout fishing if it's mid-July and August when a lot of times the conditions aren't that great for trout fishing anyway.

However, many O&Gs expressed that this is not a very popular strategy because there is much less demand from clients.

5. Discussion

The goal of this study was to explore how shifting runoff cycles affect the broader components of a river system, including the human populations who benefit from the services provided by that river. Specifically, we had three goals: 1) determine if people perceive changes in the runoff cycle; 2) identify impacts of changing runoff; and 3) if impacts are occurring, identify what adaptations strategies are being used to mitigate them.

To answer these three questions, we conducted semi-structured interviews with outfitters, guides, fisheries biologists, and researchers. Through these efforts we gained a better understanding of individuals' perceptions of changing runoff; we also identified a variety of ways shifting runoff cycles have and are affecting river ecology and use. The data also revealed a variety of adaptation strategies used by O&Gs to combat these changes. Each section below outlines our major findings, how they fit within existing literature, and a discussion about their implications.

5.1. Question 1: Perceptions of Changing Runoff

Most of our respondents perceived, or were at least aware of, long-term changes in the Yellowstone River's runoff cycle. The changes respondents discussed were: 1) earlier runoff; 2) shorter and more intense runoff; and 3) increased annual variability (i.e., drought and flood years). Studies conducted throughout the Western U.S. have shown strong evidence that supports respondent observations.

With regards to an earlier runoff cycle, Al-Chokhachy et al. (2017) found through their analysis of USGS stream data from the Greater Yellowstone Area that there has been a substantial shift to earlier peak discharge events, reductions in summer minimum streamflow, and an overall reduction in stream discharge. Other studies conducted in the western United States have found similar trends as Al-Chokhachy et al. (2017). For example, Leppi et at. (2012) examined streamflow data from 153 streams across Montana, Idaho, and Wyoming, finding that over the last 50 years, 89% of them exhibited decreasing flows in the month of August, with the most drastic declines occurring in the last 8 to 10 years. Multiple studies conducted by Rood et al. (2005, 2008) found long-term declines in total stream discharge over the 20th century, with average declines ranging from 0.1% to 0.2% per year.

Issak et al. (2012) found evidence for a shorter and more intense runoff cycle by focusing on trends in stream temperatures across the northwestern United States since 1980. One of their findings was that stream temperatures in the spring were getting colder, and the other three seasons—summer, fall, and winter—were getting warmer. To explain why spring flows were trending to colder than average temperatures, the authors suggested that spring runoff is starting sooner and coming off with greater magnitude.

Finally, Al-Chokhachy et al. (2017) found increased variability in the timing of peak discharge since 1970, which strongly suggests that there is more annual variability between drought years and flood years. All of these findings support our respondents' observations that runoff is: 1) starting earlier and ending earlier; 2) is more intense than before; and 3) is more variable between drought and flood years.

Yet respondents differed in points of reference to changes in runoff. For example, researchers and fisheries managers were aware of these changes, but their knowledge of these changes came largely from stream discharge data. O&Gs differed in that their knowledge of these changes mostly came from personal experience. O&Gs that had worked on the Yellowstone the longest described these changes with the most detail and told stories about their personal experiences with these changes. O&Gs that have worked on the Yellowstone for shorter periods referred to either data and/or anecdotal stories from people who have more experience than them. However, no matter their frame of reference, respondents largely agreed that runoff has changed. Only two respondents said they have not noticed any trends in the Yellowstone River's runoff cycle, and described the whole process as cyclical with drought and flood years occurring with no distinct direction. Besides these two, all other respondents had perceived, or were at least aware of these changes. This is notable because it indicates the magnitude and speed of these changes over the last 20 to 30 years.

5.2. Question 2: Impacts from Changing Runoff

There are many factors related to shifting runoff cycles. Through our efforts, we found evidence that changes in runoff have affected river use and outfitting and guiding in the following ways:

5.2.1. Uncertainty in booking guided trips.

Respondents expressed that yearly planning and booking has become more difficult because of increased runoff variability and the possibility of tough fishing conditions in August. One respondent said, “Conditions have become variable enough that we really need to make sure that our clients stay informed.” However, there are challenges with trying to keep potential clients informed so they book trips or visit the Yellowstone during ideal conditions. For example, one respondent described that after consecutive drought years, clients become “gun-shy” about booking trips in August, even when conditions are expected to be good. Business in August of 2017 when fishing conditions were good suffered because the previous two years had poor August conditions. Flood years have also affected bookings. As one outfitter said about 2011, they were not “able to get on the river until almost the beginning of August because of a very heavy snow year.” In 2011, trips scheduled in July had to be canceled or rescheduled because the water was too high to fish. To sum up the issue with variability, one outfitter said the following,

> It seems like, yeah, we have had a big water year, and then a few drought years, and now we have a huge snow pack this year (2017-2018 winter). So the thing is, somebody that came the 25th of June and probably had great fishing on the Yellowstone, Lord help the outfitter that tells them to come back the same time this year.”

While O&Gs can do their best to inform client expectations, variable conditions are beyond their control and can lead to reduced certainty in.

5.2.2. Altered fishing conditions.

The biggest impact we identified from an early runoff is that it often leads to low and warm flows in the later part of the summer, which adds stress to coldwater fish species and negatively affects fishing quality. As water temperatures reach or exceed 70° F (21° C), many O&Gs said fishing slowed way down. In support of this, De Staso and Rahel (1994) found that Colorado River Cutthroat Trout (*Oncorhynchus 38larkia pleuriticus)* changed their behavior and ate less frequently when water temperatures reached 20° C, which would result in fish being more difficult to catch.

A large concern is that if these documented trends of earlier runoff, lower August flows, and warmer water temperatures continue (see Al-Chokhachy et al. 2017; Leppie et al. 2012; Rood et al. 2005 and 2008; Issak et al. 2012), low and warm flows are going to become more common and more severe during August. According to Leppie et al. (2012), the trend of declining August flows has accelerated over the last decade. This trend will only continue to make fishing conditions more difficult in the late summer months. As one respondent said he used to tell people "put yourself in the middle of August for the good hopper fishing." However, with the recent trends in river conditions, he followed that statement with, "I would be a lot more cautious in giving that advice now."

5.2.3. Increased fishing pressure.

We also found evidence that increased annual variability has directly affected river use. One respondent said, "We certainly had light years before and heavier years before, don't get me wrong on that, [but] I have seen more extremely high crests [in runoff] since 1988 than I have experienced in my [30 years of] experience prior to 1988..." The respondent's observation is supported by previous research. Specifically, Al-Chokhachy et al. (2017) looked at stream data from 1930 to 2015, finding increased interannual variability in these data since 1970, which suggest a higher variation between drought and flood years. Issak et al. (2012) also observed colder than average spring runoff, which they attributed to the runoff coming off faster and with greater magnitude, essentially squeezing a normally drawn out process into a shorter timeframe.

5.2.4. Changes in aquatic insect life.

Many respondents identified changes in the aquatic macroinvertebrate population. The two main changes identified were: 1) reductions in overall abundance; and 2) changes in hatch timing. Respondents were able to provide a significant amount of descriptive detail with regards to species, timing, and their overall personal observations. Yet, even though respondents widely identified these trends, there is a lack of data or specific information about this seemingly well-known phenomenon.

Fisheries biologists were aware of these changes, but they had no data on which to base these personal observations. We do not mean to imply causality, as we do not know if changes in runoff are causing these declines in species abundance or hatch timing. However, relationships between water temperature/quality and changes in species abundance and richness have been found in previous research. For example, Durance and Ormerod (2007) looked at upland stream macroinvertebrate communities over a 25-year period (1981 to 2005). Accounting for the North Atlantic Oscillation's effects on temperature, they saw a 1.4 to 1.7° C increase in stream temperature over the 25-year period. They also found that with every 1° C increase in stream temperature, there was roughly a 21% decrease in spring macroinvertebrate abundance. These results align with respondent observations. Specifically, the reductions in abundance, as one outfitter said, "I wouldn't say they are gone, but they don't happen in the numbers that they used to." While data specific to the Yellowstone River are not available, the perceptions of respondents largely aligned with trends in other research and still has significant value.

5.2.5. Changes in species distribution.

Another issue directly tied to changes in runoff and stream temperature is species distribution. Respondents identified two species that are experiencing changes in distribution: Yellowstone Cutthroat Trout (*Oncorhynchus 40larkia bouvieri*) and Smallmouth Bass (*Micropterus dolomieu*). Cutthroat are moving farther upstream and are declining in numbers (Gunnell et al., 2008; Gresswell, 2011), while Smallmouth Bass are expanding their range and moving farther upstream (Ballard, 2017).

Yellowstone Cutthroat Trout are isolated from each other by a series of waterfalls on the Yellowstone River. The population has been declining above and below the waterfalls, but for slightly different reasons. Above the falls, declines in Yellowstone Cutthroat Trout have been attributed to predation by Lake Trout (*Salvelinus naymaycrush*), over-harvesting, whirling disease, and drought conditions (Koel et al., 2005). Respondents in this study—all of which are located below the waterfalls—mostly attributed declines to overharvesting in the 1970s and 1980s, competition between Cutthroat and non-native gamefish like Rainbow and Brown Trout, changes in hydrology and water temperature, and crossbreeding between Cutthroat and Rainbow Trout.

Research has found that stream temperatures are associated with the decreasing abundance of other coldwater fish species, like Brown Trout (*salmo trutta*) (Hari et al., 2006). On a larger scale, Wenger et al. (2011) modeled how climate change will reduce the range of trout species, and projected that by the year 2080 trout will lose 47% of their habitat in the western United States (impact to specific species on the Yellowstone River: Cutthroat Trout (*Oncorhynchus clarkia*) 58% reduction; Brown Trout (*Salmo trutta)* 48% reduction; Rainbow Trout (*Oncorhynchus mykiss*) 35% reduction).

The crossbreeding between Rainbow Trout and Cutthroat, which ultimately reduces the number of genetically pure Cutthroat Trout, is directly related to changes in runoff. Rainbow Trout spawn on the ascending side of runoff and Cutthroat spawn on the descending side, and as the runoff cycle is compressed into a shorter timeframe, there is an increased likelihood of the two species crossbreeding (Muhlfeld et al. 2009).

Another impact of the declining population is that the angler catch rate for Yellowstone Cutthroat Trout has been on a steep decline since the late 1990s, from around two fish per hour to less than one fish per hour (Koel et al. 2011). Although O&Gs in this study did not present a strong preference for one trout species over another, they noted that it had become more difficult to catch trout, and they were very concerned with the abundance of trout and the overall health of the Yellowstone ecosystem.

It was common knowledge among our respondents that Smallmouth Bass have been recently expanding their range in the Yellowstone River. One outfitter said, "Seems like there are more and more [Smallmouth Bass] every year. I caught more Smallmouth Bass in the sections I float this year than I ever have." The outfitting and guiding community has negative attitudes, or is even fearful, about Smallmouth Bass moving farther up the system. The main concern was the potential impacts bass could have on the Yellowstone Rivers trout population.

We asked O&Gs about the prospect of taking clients out to specifically target Smallmouth, and they said there is very little demand for those kinds of trips. One said, "…people always have [Smallmouth Bass] in their program, but it's never popular because people are like: Montana, *A River Runs Through It* [movie reference], trout, you know." Another said, "People are here to catch trout, in particular, large trout" when we asked him about trying to sell Smallmouth Bass fishing trips on the Yellowstone.

In addition to O&Gs saying there is no demand for Smallmouth Bass trips, most also said they just did not want Smallmouth Bass to move up the Yellowstone. For example, one outfitter said, "The thing is that I don't want that number of fish, of bass, Smallmouth Bass, in the river to the point where it is a marketable thing."

Even though O&Gs were concerned about Smallmouth Bass, managers and researchers were not. They expressed that Smallmouth Bass are considered a game species, are still far away from trout rearing areas, and that the upper Yellowstone River is bass free. When asked if Smallmouth Bass are having an impact on trout in the Yellowstone, one manager said,

> That's the piece that is kind of unknown right now. Clearly they are a top predator and like to eat smaller fish. They are pretty opportunistic feeders.

> We haven't seen anything, especially up here. The report of abundance is so low on bass that there really hasn't been much of an effect here. As you move downriver there is quite a bit of overlap and bigger numbers, and as far as I know those guys aren't seeing any indication or trends at this point. They haven't seen an effect. There certainly could be, again, because they're a predator.

Managers and researchers pointed to Smallmouth Bass as an important sport fish in the lower reaches of the Yellowstone River around Billings, Montana. Given that they are not seen as a threat, it is unlikely that any action will be taken to limit Smallmouth Bass until an issue is more explicitly identified. Even then, there will most likely be debate around potential actions given their value as a sport fish.

5.2.6. Disease Outbreaks.

The PKD outbreak in 2016 was a scary event for all the respondents. One outfitter said they "literally [saw] dead fish pretty much all the time." One of the reasons for closing the Yellowstone River after the PKD outbreak started was because there were concerns of spreading the parasite to other rivers (Opitz and Rhoten 2017). However, since the outbreak the overall concern for PKD is much lower because of recent findings. For example, one researcher said,

> Every river we have collected healthy fish from in Montana, we have found evidence of the parasite. Now we have a lot of rivers that in 2016 had comparable conditions as the Yellowstone, yet no one saw 10,000 dead fish. We have also documented now, through our archive samples, that the PKD parasite has been present in [the Yellowstone River] since at least 2011 to 2012… We were able to extract DNA from samples two months ago that were from 2011 and 2012, so [the parasite] has been there since at least then. We have had a handful of low-flow years. Then in 2017, we got another fish kill in August. So putting all the evidence together you can get fish kills outside of stressful conditions. Just because you have stressful conditions and the presence of the parasite, you don't always get a fish kill.

Researchers are currently investigating what causes PKD outbreaks, and why some outbreaks are more lethal than others. Given all of the recent discoveries about PKD, especially knowing that PKD is not entirely novel to Montana, future responses to a PKD outbreak will most likely be less severe than the response to the outbreak in 2016.

5.2.7. Imposed fishing regulations.

Hoot-Owl regulations are a direct, management implemented strategy aimed at reducing the impacts of drought conditions on fish. The impacts from the Hoot-owl regulations themselves are relatively small. One guide said this when describing the impacts of the Hoot-owl regulations, “The hoot-owls aren’t terrible because people are still out here. Everyone just quits early and they are still out at the hotels and everything like that. They are still going to dinner.” O&Gs have been able to adapt to these regulations and work around them quite well, and there is actually a high level of support for the Hoot-owl restrictions among the O&G community. However, when describing the river closure, this guide continued by saying when the “entire river is closed like last year, some of the best restaurants in town were just dead. The hotels were dead. That was different.” The impacts from the full river closure were pretty great. A report estimated that Park County, Montana—where the upper-Yellowstone River is located—lost between $359,750 to $523,815 of potential revenue during the 2016 river closure (Sage, 2016). At this time, it seems unlikely that future outbreaks of PKD, if/when they happen, will be met with such drastic actions as in 2016. Therefore, it is unlikely a full river closure—at least a PKD related closure—will happen in the future.

5.3 Question 3: Adaptation Strategies

When the Yellowstone River and its tributaries are running low and warm, respondents described having to adapt to drought conditions. The strategies used by O&Gs to combat the effects of changing runoff cycles and drought events were: 1) altering catch-and-release practices; 2) temporally shifting trips; 3) spatially shifting trips; 4) drought anticipation; and 5) targeting warm water species. These adaptations have three underlying motivations, which are reduce economic losses, provide a quality fishing experience, and protect fish populations. For example, when O&Gs alter their fishing practices when the water is warm (i.e., using heavy tippet, reeling fish in as quickly as possible, not allowing clients to take pictures of fish, releasing fish quickly, etc.) they are trying to reduce the stress placed on fish as much as possible so they do not die after being released.

The main goal for shifting trips spatially and/or temporally is to find colder water temperatures where fish are likely less stressed. To reduce stress on fish and provide clients a quality experience. Guiding during times, or in places with colder water also decreased the chances of released fish mortality, but it also offers clients opportunities to pursue fish that are not stressed, which generally means they are more likely to take an angler's fly or lure. The combination of all of these factors create a higher quality experience for clients while also reducing resource impacts.

Drought anticipation was also motivated by resource protection and providing a quality experience. Only one outfitter we spoke with heavily relied on this method, which consisted of assessing snowpack and strategically booking trips around an anticipated early runoff and August fishing restriction. This strategy was quite effective, and from our conversations, seemed to be associated with the smallest economic loss. However, this outfitter did not own a fly shop, and was able to move and schedule trips outside of the Yellowstone Watershed. People with fly shops tended to be hit harder because they were not able to pack up and move and work on a different river. They were able to send their guides to other rivers, but the revenue generated by in-store sales crashed during the closure. Shop owners also have more overhead costs than a transient guide, which made the closure harder on them. To reduce economic impacts, provide a quality fishing experience, and protect fish populations, most O&Gs use a combination of these strategies to make it through drought events.

Targeting warm water species, although it seems like a logical strategy when drought conditions make trout fishing suboptimal, is not commonly used by O&Gs. They described their willingness to target warm-water species, but they also said there is very little interest from clients. Many respondents said something to the effect of ‘people come to Montana to fish for trout.’ It does seem like there has been an increase in interest to target warm-water species like Smallmouth Bass and/or Carp with a fly, but from our conversations with the O&G community, this does not seem to be an effective adaptation because there is a lack of interest from the majority of clients.

Overall, O&Gs have adopted several strategies to adjust to changing river conditions. The three main motivations for these adaptations were reduce economic losses, provide a quality fishing experience, and protect fish populations. O&Gs expressed a deep desire to protect the Yellowstone River and the fishery. They were largely aware of their own impacts and altered their practices to reduce these impacts as much as possible. From our conversations, it seems that O&Gs have largely been able to adapt to these changes, and create a balance between business and resource protection.

6. Limitations

Several limitations of this study should be noted. First, we were working with a small sample size, which can be problematic given the extent of the Yellowstone River and the variety of stakeholders and interests involved in its broader social-ecological system. However, given our focus (i.e., looking at the perceptions and impacts of changing hydrology and the adaptations used by anglers and the outfitting and guiding industry), the population of interest was relatively small, and we contacted all respondents that were provided to us. Also, we reached theoretical saturation because toward the end of the interview process we continued to hear the same themes, and no new information was being provided.

In qualitative data collection, there is also an inherent balance between sample size and depth of the interview. Because we were using an inductive approach and working with a relatively small population, we were able to explore more concepts and in greater depth given our ability to devote more time to individual interviews. The length and detail of each interview, if expanded to additional participants, would likely have prohibited our ability not only to conduct a large number of interviews if more potential participants could have been identified, but also the effectiveness of our analysis in winnowing a larger dataset to meaningful and relevant themes.

7. Future research

This study focused on the most knowledgeable and experienced people we could find to shed light on the following questions: Are people perceiving changes in runoff; are there impacts from shifting runoff; and what adaptations are being used. We found this particular collection of ‘experts’ perceived changes, are being impacted by these changes, and are trying to adapt to them. The next logical questions is to see if the broader angling community is noticing these shifts in runoff, are being impacted by these shifts, and are employing adaptation strategies to manage them. There is also the question of whether anglers are being displaced by these shifts in runoff. If they are, where are they going and can these places handle increased use? In addition, there is the question of whether the general angling public is concerned about high water temperatures, the impacts to fish, and are these anglers altering their angling practices to reduce their impacts during stressful conditions like outfitters and guides are.

The Yellowstone is a large, relatively unaltered, wild river. Given this, it is most likely affected differently from shifts in runoff than other more managed river systems. Are managed systems more or less resilient to shifting runoff than unmanaged systems? Multiple respondents described moving their guiding operations to the Big Horn River, which is dammed. An interesting comparison study could help give direction on where to focus angling attention during stressful conditions.

8. Conclusion

Runoff cycles are shifting throughout the western United States, with widespread and varied ecological and social effects. The purpose of this study was to document if people perceived changes in runoff, if/how changing runoff has affected the social and ecological components of the Yellowstone River, and if/how people are adapting to the challenges associated with drought conditions and changes in runoff. We were able to identify that: 1) people are perceiving the recent shifts in hydrology (i.e., earlier runoff, shorter and more intense runoff, increased annual variability, and warmer water temperatures); 2) there are social and ecological impacts from these shifts; and 3) people are employing strategies to help them cope with these changes. We were also able to corroborate the information we gathered from our interview with information documented in peer-reviewed scientific literature. While O&Gs describe that fishing on the Yellowstone is still good, and that many effects of runoff changes have been manageable, if trends continue, and drought conditions become more frequent and severe, that might not hold for the future.

Ultimately, there is a shrinking resource with many increasing demands. Recreational use of the Yellowstone River has been increasing sharply over the last decade, and lower flows and higher temperatures are affecting the resource and, at times, the angling experience. Although these changes are gradual, they are occurring, and many a little faster than most of us want to believe, as one outfitter said,

> Twenty years ago I kind of looked at [climate change] and thought, boy, if I had grandkids, I'd be a little bit worried about how it's really going to change the fishing. Now, it's like screw the grandkids, it's like what is happening to me! It really seemed like a lot of this would be slow incremental changes that you really try, I was thinking, probably really won't notice that big of a change from now until I am done fishing, but the next couple of generations really will, and boy, it seems like the changes have come much faster than I have ever imagined.

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CHAPTER III

A SOCIAL-ECOLOGICAL FRAMEWORK FOR SALMON FISHERIES: A CASE STUDY OF THE KENAI RIVER (ALASKA, USA)

Abstract

The current methods used to model social-ecological systems limit the comparability, scope, and utility of social-ecological models. This is because social-ecological system modeling lacks a common fundamental structure. To address this issue, we illustrate how a foundational social-ecological systems framework can be used to build social-ecological models with an intent to increase their comparability, scope, and utility. Using Fuzzy Cognitive Mapping and the foundational structure, we collaboratively built social-ecological models with stakeholders within the Kenai River salmon fishery. Individual social-ecological models were then combined into one aggregated model representing the system's structure and function. The result is a model that can: 1) illustrate the breadth and interconnectedness of a social-ecological system; 2) be used to facilitate discussions around management; and 3) be used to explore the components and interactions that move a system toward or away from sustainability. Using the model of the Kenai fishery, we identify how the nature of salmon (migratory) and their habitat (large and unpredictable) leads to uncertainty about effective management strategies. This uncertainty, in addition to a large and diverse set of resource users, creates conflicting management visions which ultimately paralyzes a governance system operating under collective-choice rule.

1. Introduction

Salmon have endured many changes and disruptive events throughout history. Climate change, as well as landscape-scale disturbances such as glaciation, wildfires, and floods have all altered salmon abundance (Augerot and Foley, 2005; Waples et al., 2008). However, these disturbances may pale in comparison to those caused by humans. From European settlement to the 1800s, the once plentiful Atlantic Salmon in the eastern United States were nearly eradicated (Lichatowich, 1999). When white settlers made it to the West Coast, they found bountiful natural resources that had been utilized and managed by native peoples for thousands of years (Norgaard, 2019). Once this discovery was made, it did not take long for settlers to repeat the process and dramatically impact Pacific salmon as well (Lichatowich, 1999). The culmination of unsustainable harvest, habitat fragmentation, and habitat degradation has driven Pacific salmon to a small fraction of their prior abundance (National Research Council, 1996; Lenders et al., 2016, Lichatowich, 1999). Compared to historical estimates, current Pacific salmon returns in California, Idaho, Oregon, and Washington are around 6-7% of what they once were (Gresh, Lichatowich, & Schoonmaker, 2000).

In response to this decline, a great deal of effort has been devoted to stabilizing Pacific salmon populations, and in some cases restoring abundance. However, despite dedicated efforts and difficult compromises (see Brown, 2005), many salmon populations—especially Chinook Salmon populations—continue to decline (Lewis et al., 2015; Welch, Porter, & Rechisky, 2021). Many users often point a finger at 'others' to blame for the poor state of salmon. However, there are many complex and interconnected reasons why a large proportion of salmon populations continue to suffer. In addition, not all salmon populations are facing the same set of challenges. For example, dams and habitat degradation are major factors in California, Idaho, Oregon, and Washington, but many of the rivers in Alaska offer high-quality habitat and are undammed, and despite this, some salmon populations in the state are far below their historic abundance and continue to decline. Still, some salmon populations such as sockeye and pink salmon are doing relatively well. The species-specific health of salmon illustrates the complexity of understanding salmon, what affects their sustainability, and how they can, or should, be managed.

One of the largest challenges in sustainably managing salmon is their complex life cycles. While other resources like timber, for example, are stationary and visible throughout their life cycle, salmon inhabit incredibly vast amounts of space and diverse habitats. Streams, rivers, estuaries, and the ocean all play a critical role in salmon development and survival, and a disruption in any one of these systems may have detrimental effects on entire populations. In addition, humans not only alter and affect all these systems, they also harvest salmon—intentionally and unintentionally—as they migrate throughout their life. Therefore, when trying to understand salmon, it is important to identify and explore the social and ecological forces that affect their health.

Social and ecological sciences have developed separately, and in many cases, it is difficult to combine the two (Norgaard, 2008). However, salmon inhabit a complex system comprised of both social and ecological components. Given this, taking a social-ecological approach to understanding and managing the species is necessary. Social-ecological systems research is founded in the idea that to address the complex challenges we face in managing natural resources today, we must find ways to integrate a diverse scope of knowledge (Ostrom 2007; 2009). Given the complex social and ecological dynamics surrounding salmon, it would be useful to have a unifying framework to organize our understanding of the species, their habitat, human and environmental stressors, and their management. Our goal in this research was to develop this framework. Using fuzzy cognitive mapping and input from key stakeholders involved in the Kenai river salmon fishery, we develop a social-ecological systems framework of salmon fisheries.

Our goals through this effort are to make three contributions to 'how' and 'what' we know about salmon fisheries. First, we outline a method for creating social-ecological models using a fuzzy cognitive mapping approach based in Ostrom's (2007; 2009) social-ecological systems framework. Fuzzy cognitive mapping is a useful tool for modeling the structure and function of social-ecological systems. However, standard practice for using the method requires participants to develop models without a clear framework to help identify and organize variables (e.g., Özesmi and Özesmi, 2003; 2004). Fuzzy cognitive mapping can benefit from the integration of Ostrom's social-ecological systems framework in three ways. First, the framework could reduce the burden placed on participants that may be unfamiliar with modeling and/or the formal concept of social-ecological systems. Second, the framework could increase the likelihood that important components and relationships are not excluded. And third, the framework could help structure social-ecological system models in a way that improves the comparability and/or integration of models across different systems. Ultimately, the framework can benefit individual mapping and modeling efforts, as it has the potential to deepen our understanding of the structure and function of social-ecological systems more broadly.

Our second contribution is focused on 'what' we know about salmon fisheries. Understanding the complex social and ecological components and dynamics of a salmon fishery is essential to addressing the challenges they face. Therefore, we wanted to develop a framework that can be utilized in two ways. First, as a tool for illustrating the breadth and interconnectedness of the social and ecological components of a salmon fishery. We wanted to provide detailed information about each component within the system and their interactions with one another. Mapping out the social-ecological system of salmon fisheries could be useful for a broad range of people, including students, policy makers, and resource managers. Second, we wanted to develop a framework that could be used to facilitate discussions around salmon management. For example, if the framework can be used to evaluate how a disturbance event, such as fire, may affect a fishery, managers can systematically explore how each component of the system may be affected and subsequently identify priorities and develop plans to respond to such events.

The third and final contribution is to illustrate how mapping a social-ecological system can be useful in identifying constraints for sustainable management. Ostrom (2009) used the social-ecological framework to identify a set of variables that can help predict the likelihood of a system self-organizing to create sustainable management. In the discussion, we use these same variables to illustrate how they still affect a social-ecological system's ability to be sustainable after the system has already self-organized.

2. Related Literature

2.1 Fuzzy Cognitive Mapping

Fuzzy cognitive mapping is a method used to organize and depict the *structure* and *function* of a system. Kosko (1986), who developed the method, argued it is useful for modeling the structure and function of broad systems with uncertain (i.e., fuzzy) components and/or relationships. Ultimately, the method consists of asking knowledgeable people to map their understanding of a particular system, and individual maps are combined into one model that represents that system. Gray et al. (2013) describe fuzzy cognitive mapping as a "complex form of data collection where […] participants are asked to develop qualitative static models which are translated into quantitative dynamic models" (p. 967).

Since its inception, fuzzy cognitive mapping has been used across a wide geographic and topical range. For example, it has been used in environmental planning initiatives in Turkey (Ozesmi and Ozesmi, 2003) and to understanding the complexities behind species conservation in Tanzania (Gray et al., 2015). The method has also been used by a range of professionals, including engineers (Amer et al., 2011), physicians (Benbenishty, 1992), fishermen (Mackinson, 2000; Wise et al., 2012), and environmental managers (Gray et al., 2013; 2014), amongst others.

2.2 Social-Ecological Systems Framework

Given the breadth and complexity of social-ecological systems, Ostrom (2007; 2009) argued that a general framework was needed to organize information so that knowledge generated in any one discipline or set of disciplines can be made relevant to those in other fields. This is important because ecological and social sciences have, for the most part, developed independently and are difficult to integrate with one another

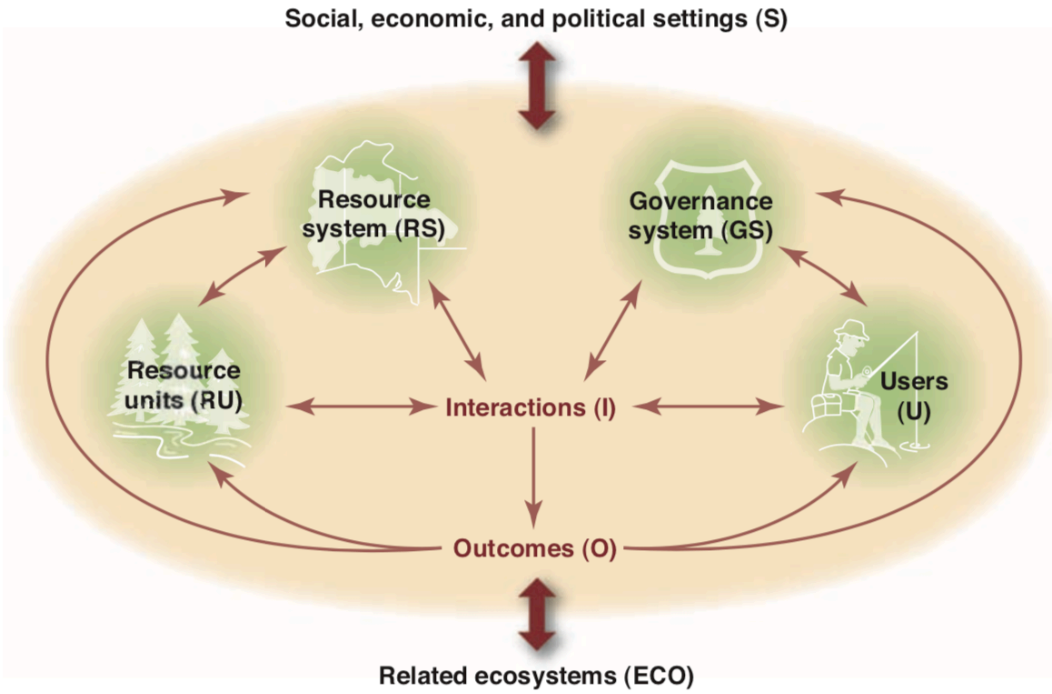
(Norgaard, 2008). The core of Ostrom's social-ecological systems framework (2007; 2009) is a set of four first-level variables: 1) Resource System; 2) Resource Units; 3) Governance System; and 4) Resource Users (Figure 1). All social-ecological systems have these four sets of variables. Ostrom (2007) describes these first-level variables as "decomposable," meaning they can be broken down into many second-level variables representing the structure of a particular system and the research question being addressed. Given all social-ecological systems have these four first-level variables, it makes sense to use them as the fundamental components around which maps and models of social-ecological systems are developed.

2.3 Using Fuzzy Cognitive Maps to Examine Social-Ecological Systems

Fuzzy cognitive mapping can be a particularly useful tool for developing an understanding of complex social-ecological systems because it: 1) can be used to map the structure of a system; 2) can be used to facilitate the sharing of information between stakeholders; 3) can open up the possibility of analyzing the functions of the system through hypothetical and simulated scenarios; and 4) can be used to examine how

Figure 3.1.

Ostrom's Social-Ecological Systems Framework



changes in any one particular variable or a set of variables may move the system toward or away from overall goals (Gray et al., 2015). However, many if not all research and planning efforts using fuzzy cognitive mapping lack a consistent and systematic framework, limiting their ability to develop generalizable models capable of being transferred and compared across contexts. Here we detail how a basic social-ecological systems framework can be used to improve fuzzy cognitive mapping of complex social-ecological systems. Then, we review the salmon fishery social-ecological systems framework that was developed using this method.

3. Methods

3.1 Overview

We used a participatory method to identify important variables and interactions (Gray et al., 2013). This involved interviewing key stakeholders and facilitating the construction of individual fuzzy cognitive maps (Kosko,1986; Ozesmi and Ozesmi, 2003; 2004). Each fuzzy cognitive map was built using the Ostrom's social-ecological systems framework (Figure 1; 2007; 2009). We used the software Mental Modeler (Gray et al., 2013) to build individual and consolidated fuzzy cognitive maps. Lastly, we went through a validation process with stakeholders to test the model's accuracy and function. Each of these steps is detailed below.

3.2 Participatory Method

There are two different ways in which models can be built using the participatory method. The first method involves stakeholders largely building the models themselves with some guidance from researchers/planners. The second method, which we used, involves the researcher being an active facilitator in the model building process (Gray et al., 2013; Ozesmi and Ozesmi, 2003; 2004). The facilitator method is advantageous for four reasons. First, it reduces the participants' burden of having to understand the method, learn the software, and complete the model, which ultimately increases efficiency, reduces frustration, and provides incentive to stick with the process until it is complete. Second, facilitation can create consistency in the model building process by guiding participants in a methodical and consistent way. Third, facilitation allows for model corrections that may create issues later in the research. For example, interviewees could list second-level variables like *salmon* that are open to interpretation. *Salmon* could refer to salmon return, salmon harvest, salmon escapement, etc. Being able to ask interviewees exactly what they mean greatly improves the accuracy and usefulness of the model. Fourth, facilitation reduces the assumptions made by researchers later on. Being an active participant in the building of each model provides context behind each variable and connection. This context is important when consolidating individual models into a combined model and improves the researcher's understanding of the system as a whole. Overall, the facilitator approach improves the quality of the model and the researcher's/planner's understanding of the system and the issues it faces.

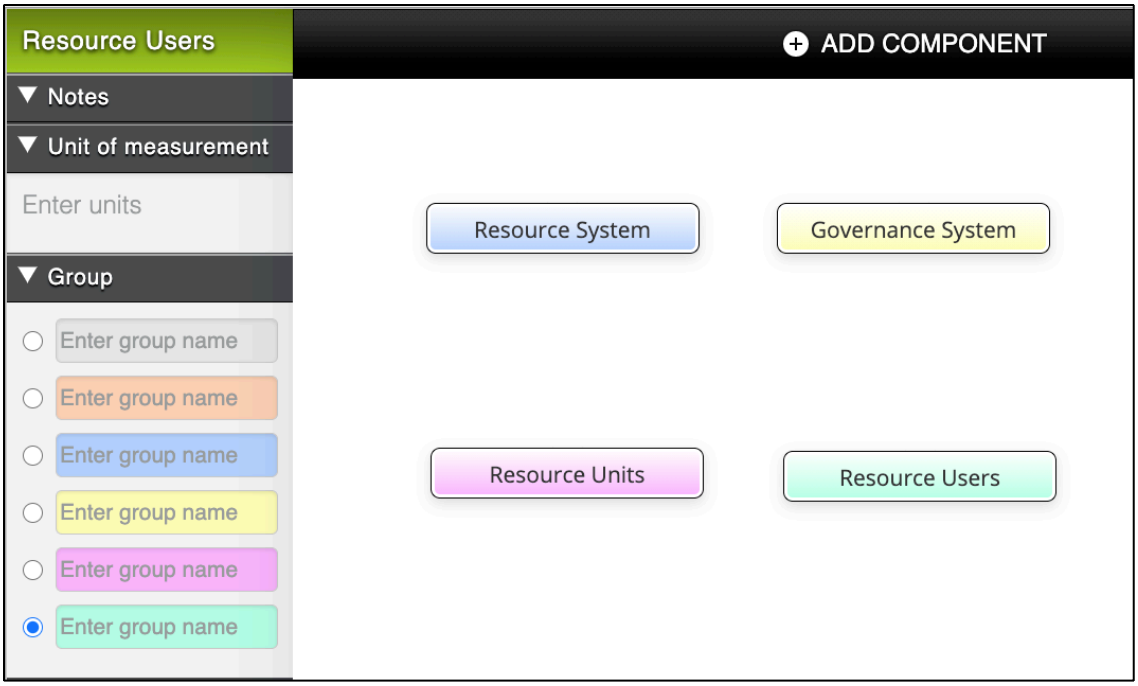
To build individual fuzzy cognitive maps, we sought out knowledgeable stakeholders who had some knowledge about the functions of the study system broadly as well as stakeholders who had specific expertise in the interactions of individual components within the system. Interviewees included federal managers, state managers, advocates, people from non-profits, and business owners (from commercial and sport fishing backgrounds). We specifically sought out people who had long periods of experience dealing with the system. We utilized a chain-referral sampling method to identify additional interviewees at the end of interviews.

3.3 Social-Ecological Systems Framework

The four first-level variables in Ostrom's social-ecological systems framework (2007; 2009) provided a common foundation from which individual interpretations of the study system was built. Without this foundation some participants may neglect adding important components, which could minimize the understanding of unique interactions

Figure 3.2.

The Four First-Level Variables, as Seen by Participants at the Beginning of the Facilitated Model Building Sessions



and complexities within the system. To help orient participants at the beginning of each interview, we listed and described each first-level variable to interviewees (Figure 2), and then worked with them to identify key second-level variables within each of the first-level variables. After several initial interviews, we found it was easiest for participants to identify second-level variables within *resource units* and *resource users*, so we began there for all subsequent interviews. The *governance system* tended to be the most difficult for participants to operationalize.

3.4 Fuzzy Cognitive Mapping

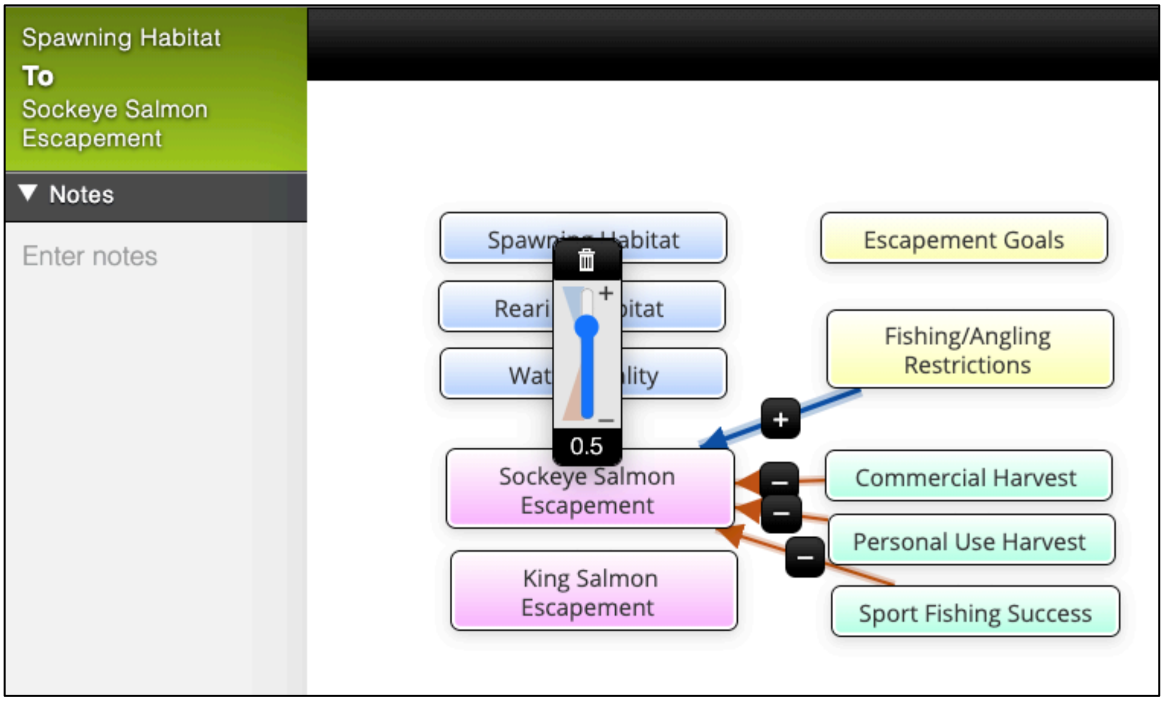
Fuzzy cognitive maps have two main components, which are *variables* and *interactions*. Variables can be well-defined and measurable, such as stream flow, or they can be more nebulous, like people's well-being. In the process of building fuzzy cognitive maps, a person or group decides what variables best define the major components of a particular system. In our work, we provided the first-level variables to interviewees and asked them to identify relevant second-level variables.

Once a set of second-level variables was chosen, we asked the interviewee to describe causal interactions between variables, which usually started with the most obvious and moved to the more complex and nuanced. Once an interaction was identified, interviewees were then prompted to describe the direction (from one variable to another), nature (positive or negative), and strength (e.g., high, medium, or low) of the relationship[1]. Figure 3 shows an example of second-level variables, and some of the connections that would be made between them that a participant could have identified. Throughout this process, models are manipulated by interviewees (e.g., second-level variables were split and consolidated, the directionality of relationships were changed, etc.). These model building exercises are time-consuming, and far more involved than a normal interview because participants are transforming their understanding of a complex system into a consolidated set of variables and interactions. Our work followed the guidance of Ozesmi and Ozesmi (2003; 2004) and readers are referred there for further details on building fuzzy cognitive maps with interviewees.

[1] There are different approaches to determining the strength of relationships in these models, and the approach is predicated on the scope of the model and certainty of relationship strength. For example, we chose to use 'high,' 'medium,' and 'low' measures of relationship strength because the scope of the model was so large and the precision of relationship strength for many relationships were difficult to quantify. Therefore, we placed more emphasis on the direction of interactions, the nature of them (positive or negative), and some general degree of strength. If working on a model with a smaller scale and more precise data related to the strength of interactions, the Mental Modeler software allows for this level of precise to be represented.

Figure 3.3.

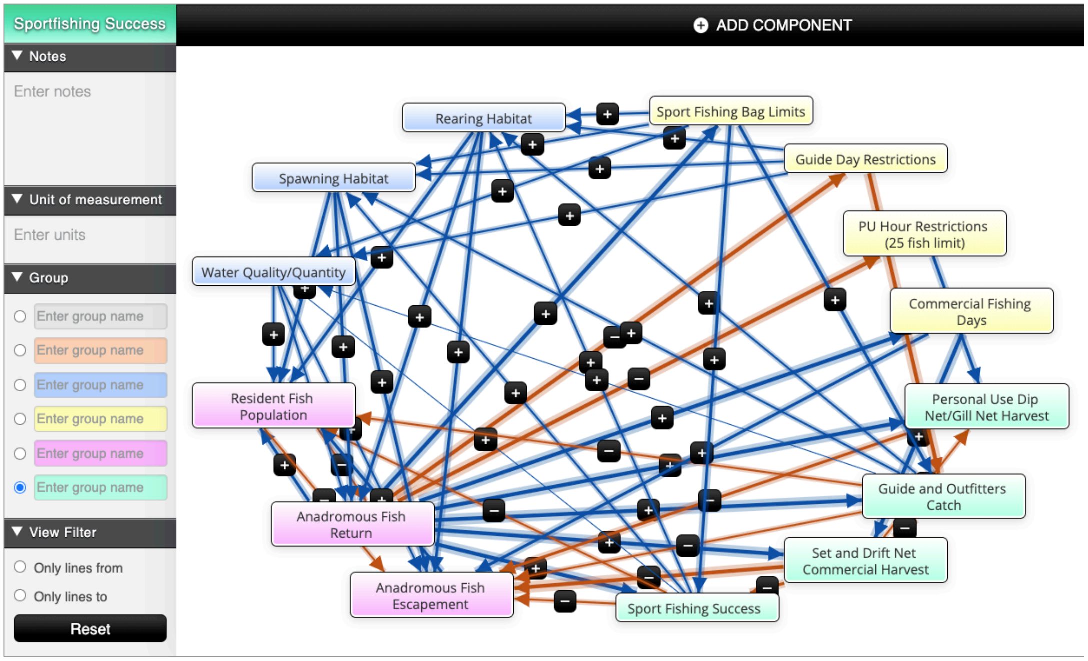
An Example of Second-Level Variables with Connections



We interviewed ten people in an initial round of interviews. The average time it took for an interviewee to complete a fuzzy cognitive map was 2 h and 9 m (the minimum interview time was 50 m and the maximum was 4 h and 12 m). Consistent with previous research (Colwell, 1997; Osezmi and Osezmi, 2003; 2004) suggesting many people have a shared understanding of a system, the number of new concepts introduced into the models quickly diminished with the number of interviews we conducted. Therefore, we concluded the first round of data collection once we had a good representation of stakeholders and the number of new variables introduced diminished. Figure 4 shows an example of a fuzzy cognitive map completed by one interviewee.

Figure 3.4.

An Example of a Fuzzy Cognitive Map Completed by an Interviewee



3.5 Building a Combined "Social" Cognitive Map

Qualitative or quantitative aggregation can be used to combine individual fuzzy cognitive maps into one consolidated social model (Osezmi and Osezmi, 2003). We chose to use qualitative aggregation because we had a limited sample size, a diverse representation of backgrounds and specialties, and a great deal of context provided in the interviews that we wanted to include.

Gray and others (2013) provide an outline for qualitative aggregation, which includes creating a simple matrix with all variables identified by interviewees, and then averaging the strength of relationships between them. In our initial attempt we found many second-level variables could be categorized into common themes. Ozesmi and Ozesmi (2004) note that "maps with over 20-30 variables start being counterproductive for gaining insights" (p.53) and recommend having approximately 12 variables for the analysis (Buede and Ferrell, 1993). Therefore, we underwent a process of grouping similar variables into common themes to reduce the number of similar, but uniquely named second-level variables.

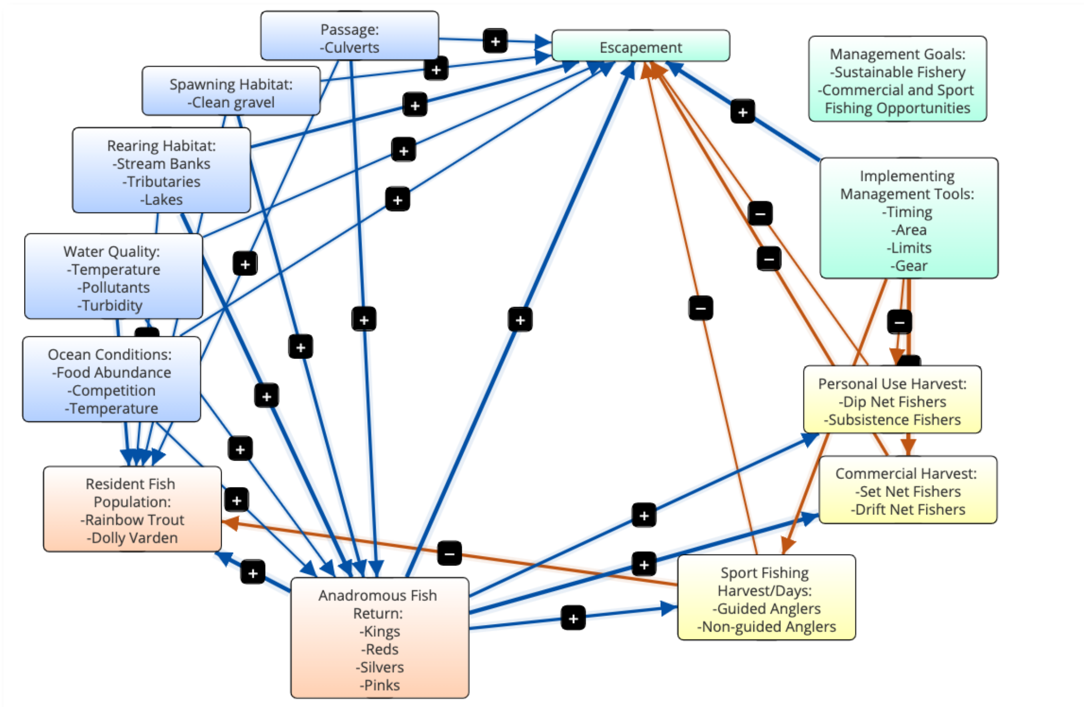
The first step was to create a list of all second-level variables grouped by the four first-level variables. Once these lists were made, we then proceeded to group them based on their commonality. Once we had a list of condensed second-level variables, we proceeded to map the interactions. This process again involved looking at individual models and listing the direction, strength, and nature of interactions. Once a list was developed, we averaged the interactions between variables. We continued this process until a consolidated model was complete.

This process heavily relies on qualitative methods, many of which are grounded in the processes described by Corbin and Strauss (2008). However, instead of reading transcriptions of interviews and looking for common themes, we were examining interviewees' description of variables and interactions that can be consolidated into a more functional and interpretable model.

These models, like every model, are an attempt to represent how a system or process functions. All modeling approaches have tradeoffs, and this approach is conducive to building a high-level model using variables that may or may not have empirical data which could be used in a quantitative model. It is important to note the process of model consolidation is intended to yield a common representation of the system and its interactions. This representation was fine-tuned with additional information from other data sources and subsequent interviews with stakeholders. The first version of the aggregated social-ecological system model is presented in Figure 5.

Figure 3.5.

The First Version of the Aggregated Social-Ecological System Model



3.6 Model Validation

The final step in our process was model validation. We did this by conducting a second round of data collection which consisted of reviewing the model with people who we interviewed in the first round of data collection in addition to interviewing additional stakeholders. This second phase of data collection consisted of presenting a printed version of the aggregated model to interviewees, and then asking them to critique the model. We provided markers for the interviewees and encouraged them to write on the printouts. Each interview was recorded so we could refer to conversations if needed. We interviewed 11 people during the validation process. Interviews ranged from 1 hour to over 3 hours, and the average interview lasted approximately 90 minutes.

Validation interviews usually focused on more nuanced aspects of the model reflecting each interviewees' background and knowledge of the system. None of the interviewees heavily critiqued the model, but they did provide valuable input which improved the model's representation of the fishery.

The validation process also presents an opportunity to ask very specific questions about how the fishery functions. Before each interview, we generated a list of specific questions we assumed the respondent would be able to help answer. The combination of openly reviewing the model and asking specific questions led to constructive conversations and valuable input.

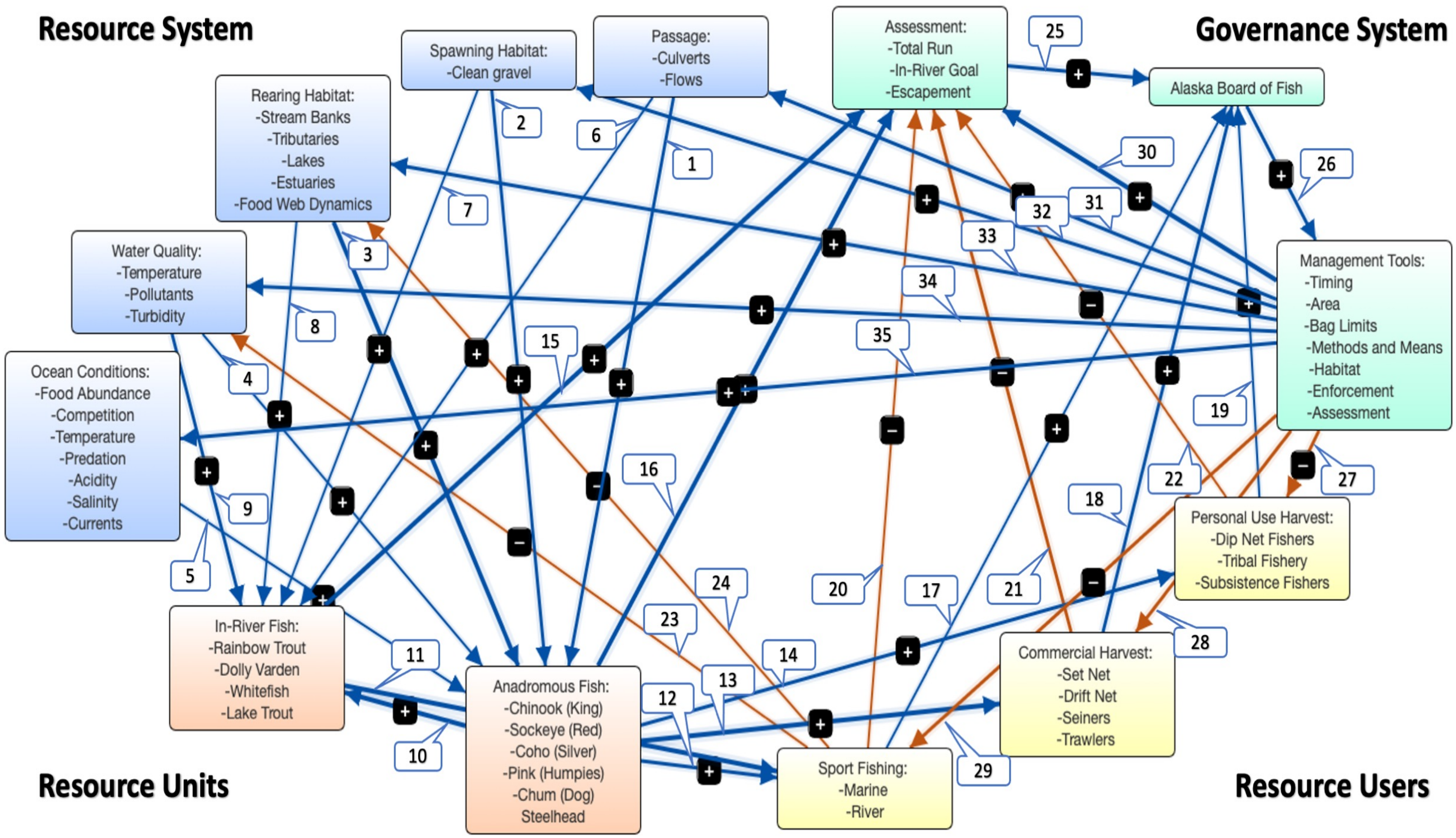
Once we had finished the second round of data collection, we went through each printout and reviewed the recorded conversations. Through this process we added to and manipulated the model to best reflect the input we were given. The final version of the salmon fisheries social-ecological model is presented in Figure 6.

3.6 Literature review of second level variables

After the aggregated model was finished, we conducted a literature review focused on the second level variables in the model. Using the aggregated map to guide the literature review helped solidify and expand on many of the points interviewees made. Throughout the results, we incorporated literature to support concepts and/or phenomena that interviewees described. We also produced a supplementary document that contains a through literature review of all the second level variables in the aggregated model (see Supplementary Materials).

Figure 3.6.

The Final Version of the Aggregated Social-Ecological System Model with Numbered Interactions



4. Results

The aggregation of the individual fuzzy cognitive maps yielded a detailed list of second level variables organized within the first level variables of Ostrom's (2007; 2009) framework; it also yielded a web of interactions between the second level variables (Figure 6). The overall flow of the system is as follows. First, the *resource system*—the foundation of the fishery—is composed of a host of second level variables that sustain the ecological integrity of the ecosystem. The *resource system* then supports the *resource units* (interactions 1-9), which are classified into two second level variables: in-river fish and anadromous fish. Both in-river and anadromous fish are important to the fishery, but play very different roles. The *resource units* then support the *resource users* (interactions 12-14), which are broken into commercial, personal, and sport fishers. The *resource users*, overall, have a negative impact on in-river and anadromous fish (interactions 20-22), and some other components of the resource system such as streambanks and water quality (interactions 23-24). The *governance system* is more complex than the previously mentioned components because it affects, and is affected by, all other parts of the model (interactions 27-35). The governance system also has indirect and mixed relationships with other components within the model. Table 1 contains a brief explanation of each interaction in the model.

Table 3.1.

List of Numbered Interactions and Descriptions

Interactions	Description of interactions
Resource system	
1-5	Resource system supporting anadromous fish
6-9	Resource system supporting in-river fish
Resource units	
10	Anadromous fish supporting in-river fish
11	In-river fish supporting sport fishers
12-14	Anadromous fish supporting all resource users
15-16	In-river and anadromous fish assessment
Resource users	
17-19	Resource users providing input to the Alaska Board of Fish
20-22	Resource users harvesting fish. Harvest calculated via assessment
23-24	Sport fishers impacting rearing habitat and water quality
Governance system	
25	Assessment providing information to the Alaska Board of Fish
26	Alaska Board of Fish giving direction and tools to Alaska Department of Fish and Game
27-29	Management reducing harvest through timing, area, bag limits, methods and means
30	Management tools increasing total run, in-river, and escapement
31-35	Management supporting resource system

The relationships depicted in the aggregated map are direct—from one second level variable to another—but there are also indirect and mixed relationships that emerged through the interviews. We excluded indirect and mixed relationships from the map out of a desire to keep the representation of the system more interpretable and representative of the commonalities expressed across all participants. However, we do mention indirect and mixed relationships in our description of the model when appropriate. One example of a mixed relationship is between the resource users and the governance system. Directly, the governance system creates and enforces rules and regulations that restrict resource users' activities and harvest—a direct, but negative relationship (interactions 27 – 29). However, the goal of these rules and regulations is to create equitable opportunities for resource users and ensure the fisheries sustainability—a positive, but indirect relationship.

For the rest of this section, we provide a brief overview of the second level variables described by respondents (i.e., the *structure* of the social-ecological system). We focus the results presented here on describing the interactions between variables as these interactions characterize the *function* of the social-ecological system. A much more detailed description of each second level variable and the role they play in a salmon fishery is provided in the Supplementary Material.

4.1 Resource system

The foundation of the Kenai River fishery is the resource system (the blue second level variables in Figure 6). Interviewees identified fish passage, spawning habitat, rearing habitat, water quality, and ocean conditions as critical components sustaining the ecological integrity of the Kenai fishery. One important thing to note about the resource system of a salmon fishery is the wide scope of habitats salmon occupy at each stage of their life cycle. Salmon utilize streams, rivers, lakes, estuaries, and large and diverse areas of the ocean (interactions 1-5). The discussions around the variables in the resource system usually focused on their importance for salmon productivity and the challenges associated with them. For example, one interviewee was describing the impacts of drought on the fishery. They mentioned how drought can affect fish passage, saying "low water levels are going to cut off certain areas and tributary spawning locations" (see Atlas et al, 2021). In addition to passage issues, low water is also correlated with higher water temperature, which creates multiple stressors on salmon (see Marine and Cech, 2004; Singer et al., 2021). For example, one interviewee said,

> When you get water that's upwards of 19 or 20 degrees Celsius, besides being hard on adult fish, it's going to be hard on your juveniles as well.… In some systems like the Susitna [a river that drains into the Upper Cook Inlet], perfectly healthy salmon were dying because they were spawning in nearly clear water tributaries and the temperatures were getting so high that it was depleting the oxygen. The other thing we deal with is [how temperature affects] overall juvenile survival—'Parr cooking' would be one word for it.

This is just one example of how changes in the resource system affect salmon productivity. However, every component of the resource system is subject to natural, and human caused variability, and this variability affects the resource units. When the conditions are good, the resource units usually do well, but a decline in only one component of the resource system can act as a bottleneck for resource unit productivity. Some of these bottlenecks are obvious—such as cutting off sections of spawning habitat via dams (see National Research Council, 1996) or low/warm stream flows—but others are far more complicated, and we still lack a good understanding of how they affect salmon productivity. There is a relatively good understanding of variability that exists within passage, spawning habitat, rearing habitat, and water quality from existing monitoring efforts and the scientific literature (detailed information about each of these components can be found in the Supplementary Material). However, the area of the resource system that is the least understood is the ocean (interaction 5).

There is currently a basic scientific understanding of how ocean conditions affect salmon productivity. Much of the difficulty in understanding the ocean comes from the large amount of variability that exists there. Therefore, in many ways, the ocean is still a "black box." It has only been with the advent of genetic technology that we are beginning to understand where populations of salmon go when they enter the ocean (Faunce, 2015). The characteristics of ocean conditions mentioned by interviewees were food abundance, competition, temperature, predation, acidity, salinity, and currents. Climate change is one driver affecting ocean conditions. For example, climate change is affecting food abundance, water temperature, acidity, currents, and predation. To illustrate these complex interactions, one interviewee said,

> Changes in [ocean] water temperatures could influence the movement of other species which may be competing with or praying upon salmon species. For example, if we have warmer currents coming up the coast, suddenly we are seeing species that we don't typically see up here. Are they competing with the natural salmon or are they praying upon them? Are those currents or [changes in] water temperature making the salmon that spawn in Alaska go into other areas of the ocean during their ocean phase? Do they have to go deeper to get to cooler water, or are they going farther out into the middle of the Pacific? If they are going farther out, is it putting them in places where they are more likely to get intercepted by foreign fleets or big ocean fisheries?

The questions posed by this interviewee provide an example of how people are trying to understand the complex interactions taking place in the ocean, and the range of possibilities that exist. A change in one variable can have cascading effects with many possible outcomes.

There are three factors that make understanding the relationship between salmon and the ocean difficult. The first is the transitory nature of salmon. They migrate thousands of miles between the time they enter the ocean to when they return to spawn. The second is the overall size of the North Pacific Ocean. Lastly, and the thing truly complicating the matter is the variability that exists in the ocean, which is seemingly becoming more unpredictable, as one interviewee said, “The Pacific Decadal Oscillation Cycle used to be pretty predictable, but things have gotten pretty wonky since the 2000s.”

Together, these three factors make it very difficult to get a good grasp on how salmon are affected during their time in the ocean. One interviewee describes this challenge and the frustration by saying,

> To manage [salmon] with an acceptable level of accuracy and precision, you have to be able to implement in-season management tools. The feds don't mind getting involved with stuff like trees, because you can measure the biomass, you know how fast they're going to grow, and you can figure out the harvestable surplus. Halibut [are similar], to a certain extent, barring any kind of weird fluctuations. Salmon are a lot harder because they do have those weird fluctuations. Our predictive models that we use in Alaska are really good when you are in the middle of the bell curve, but when there is a deviation—when the run is late, or when the run is weak, or when the run is strong or early—that model goes out the window. It's one of those things, when you're right you're right, but when you're wrong you are very wrong. That's a real frustration you have because salmon are not as predictable for a variety of reasons. [One of those reasons is] because they migrate over such large areas.

Having a better understanding of ocean dynamics and their effect on salmon would greatly improve salmon management. As the interviewee expressed above, knowing how many salmon will return would allow the governance system to operate in a less reactionary way. Unexpected low salmon returns heavily impact the region’s economy. When resource users—particularly the commercial fishers and the sport Chinook salmon fishers—cannot anticipate their harvest, success, and access to the fishery, it creates a large degree of uncertainty and anxiety. Although it would be ideal to better understand the relationship between ocean conditions and salmon, this relationship is incredibly complex, and with the forces of a rapidly changing climate, it is also a moving target.

Interviewees also expressed concern over how hatchery produced salmon may be impacting wild salmon populations (interaction 5). There are different types of hatcheries, and each has an intended purpose—like those that were used to augment salmon production after a dam was built. Most concerning to interviewees were those in Alaska, Japan, and Russia producing salmon solely for commercial harvest. The hatchery programs between these three countries have released an annual average of 4.4 billion salmon into the North Pacific Ocean between 1990-2015 (Ruggerone and Irvine, 2018). When discussing all the variability that exists in the ocean, and how it affects salmon productivity, one interviewee said that in relation to all of those stressors, they are "more concerned about the competition [wild salmon stocks have] with [hatchery] pink salmon." Hatchery production of salmon largely began in the 1970s starting in Asia, but North America quickly followed (Ruggerone and Irvine, 2018). Because of hatchery-origin salmon, the abundance of pink, chum, and sockeye salmon in the North Pacific Ocean is higher now than at any time since the collection of relatively comprehensive statistics began in 1925; and now hatchery salmon represent approximately 40% of all chum, pink, and sockeye salmon biomass for the region (Ruggerone and Irvine, 2018). Researchers have continually found a correlation between the number of hatchery-released fish and the decline in natural-origin salmon size and age at maturity. Looking at 90-years of data, Ruggerone and Irvine (2018) found a strong negative correlation between the number of hatchery-origin salmon and average adult salmon weight and length, specifically finding that weight has gone down with the increase in hatchery fish. Other research has also found correlations between these two factors (see Debertin et al., 2017; Hilborn and Eggers, 2000; Lewis et al., 2015; Ruggerone et al., 2016; Shaul and Geiger, 2016). However, as the director of Fisheries Research of Alaska Department of Fish and Game said to the Board of Fish, "correlation is not causation" (Medred, 2021).

Recent research is documenting how interactions between the two variables are more complicated because of several confounding factors (Ward et al., 2017). Oke et al. (2021) found hatchery production alone accounted for only a small amount of the total variance in the declines of adult salmon size; however, hatchery pink salmon abundance was the only variable negatively related to salmon body size in chinook, chum, sockeye, and coho salmon. This finding, along with other research, indicates hatchery-origin salmon are likely contributing to density-dependent dynamics in the ocean.

Overall, the components of the resource system outlined in the model are the foundation of a salmon fishery. Because salmon are highly migratory, the resource system that supports them is large and diverse. Each component of the resource system plays an important role in the life cycle of salmon, and a decline in just one component can create a bottleneck for salmon productivity. Some components are better understood than others. Currently, the dynamics occurring within the ocean are the largest unknown. In addition, beyond the traditional forces humans have placed on salmon resource systems (e.g., logging, dams, water diversions, etc.), there are new and less understood human-caused forces such as climate change and hatchery produced salmon that are affecting wild salmon populations in relatively pristine habitats. Both emerging forces are raising concerns because climate change is altering various aspects of the salmon resource system, and hatchery salmon are creating more competition for food resources and habitat. Many interviewees place a greater priority on native, wild salmon populations because they believe the genetic diversity they hold will help buffer the impacts of a rapidly changing environment, as one interviewee said, “if you have good genetic stocks then there is a lot of resilience in the system.”

4.2 Resource Units

The primary focus of the fishery are the resource units (the orange second level variables in Figure 6). Interviewees made a clear distinction between in-river fish (e.g., rainbow trout) and anadromous fish (i.e., salmon and steelhead). In addition to this distinction, each species also has unique life-cycle characteristics and habitat requirements, and plays a very different role in the system, as they all have varying sport, commercial, and cultural values.

The resource system supports the resource units by providing habitat and food (interactions 1-9). All the variables in the resource system directly influence the resource units except there is not a direct link between the ocean and in-river fish, even though in-river fish greatly benefit from the ocean. In-river fish benefit from the ocean through the marine-derived nutrients that are transported by anadromous fish from the ocean to streams and rivers (interaction 10). When anadromous fish spawn, in-river fish consume nutrient rich eggs, and when salmon die, in-river fish consume their flesh and carcasses (Scheuerell et al., 2007). It is this nutrient transportation process that supports the productivity of the Kenai's in-river fish population.

Both in-river and anadromous fish are important for the fishery's resource users. However, there is great diversity in what species resource users target and how they target them. These differences play distinct roles in the region's economy and culture.

The in-river fish—rainbow trout, dolly varden, etc.—are primarily utilized by sport fishers (interaction 11). The Kenai River is a well-known trout fishery which attracts many people and supports a robust sector of the outfitting and guiding industry, with some outfitters and guides focusing primarily on trout. People target in-river fish throughout the year, but the main season starts in the spring and extends into the late-fall. Rainbow trout and dolly varden congregate around spawning salmon to eat salmon eggs. This provides high quality fishing opportunities, therefore most of the in-river sport fishing occurs in the late-summer and fall when the salmon are spawning. However, people do target trout in the spring before the salmon arrive, which helps support the local service sector.

Although in-river fish play an important role in the fishery, anadromous fish are the primary resource unit utilized by resource users (commercial, personal use, and sport fishers) (interactions 12-14). Each species of salmon is utilized differently. For example, Sockeye salmon, which arrive in early-June and run until the end of August, return to the Kenai in the millions and play the largest role in the fishery. They are the most targeted and harvested species by all user groups, and they are the primary food fish in the region (Schoen et al., 2017). In comparison, Chinook salmon, which arrive in late-May and run until August, play a much different role. Chinook are also harvested, but in much lower numbers. They are primarily targeted by sport fishers, and given current regulations, many are caught and released. Chinook salmon historically drove the largest sector of the outfitting and guiding industry on the Kenai River. However, Chinook runs have declined at an alarming rate and to an alarming level in recent years (ADF&Gd, N.D.). In addition to low returns, the size of Chinook has also been declining; however, this phenomenon is also not isolated to the Kenai (Lewis et al., 2015; Oke et al., 2021). Success rates, and even opportunities to fish for Chinook, have declined over the last decade because of low returns and regulations intended to protect Chinook salmon.

There are interactions between species that have profound effects on the fishery. For example, the commercial fishery uses nets in a variety of fashions to catch salmon. The set-net fishery, which strings nets near the coastline, intercepts salmon as they make their way back to their natal streams. These nets are indiscriminate, meaning they catch whatever swims into them. Since Sockeye and Chinook salmon run at the same time, both species are caught. Historically, this created tension between sport and commercial fishers; however, this tension has increased in recent years as Chinook have again declined to alarmingly low levels. Therefore, measures to protect the remaining Chinook include restricting both the sport and commercial fisheries, which has a huge impact on their ability to operate. In 2021, for example, Chinook returns were low—as they have been for consecutive years—and the Alaska Department of Fish and Game used their Emergency Order authority to restrict the time the commercial fishery could fish (Earl, 2021). This restricted the commercial fishery from harvesting the plentiful Sockeye salmon to reduce impacts on the declining Chinook salmon.

Segments of the sport fishing industry are also restricted because of low Chinook returns. However, sport fishing methods are more discriminant than nets. Therefore, when Chinook numbers are low, sportfishers can target other species of salmon or trout. However, culturally, there is a massive difference between catching a 6-pound Sockeye and catching a 30- to 60-pound Chinook, and people are much more willing to pay for a guide's expertise to catch a Chinook. Therefore, Chinook restrictions have a huge effect on the commercial and sport fishing industries within the Kenai.

Fisheries like the Kenai support many species of fish. Each of these species are important, however, they are important for different, and often multiple reasons. For example, Sockeye provide food and income for all resource users, and given their large return, they also play a large role in supporting in-river fish like trout. Resource users have found ways to utilize many of the species. This diversification has expanded the service industry, which has diversified the economy and created opportunities despite the decline in Chinook salmon. However, restrictions intended to protect Chinook are having large negative effects on both sport and commercial fishers. There is a lot of interest to protect Chinook because of the restrictions they impose, but from conversations, the more important reason to protect Chinook is because of what they represent biologically and culturally. The value of Chinook is reflected in the intensity of restrictions on the fishery they create. If Chinook were not as valued, the resource users and governance systems would likely not implement or tolerate the restrictions imposed to protect them.

4.3 Resource Users

Although there are clear distinctions between commercial fishers, sport fishers, and personal use fishers, there is also great diversity within each of the three groups. For example, just within the commercial fishing sector, interviewees identified set netters, drift netters, seiners, and trawlers. Within sport fishing, interviewees identified both marine and river anglers; interviewees also made distinctions between guided and non-guided anglers. The last distinct group interviewees identified were the personal use fishers, which includes dipnet fishers, a tribal educational fishery, and a small federal subsistence fishery.

4.3.1 Connections.

Resource users interact with all other first-level variables in the model. For example, resource users target resource units (interactions 11-14), which is a direct and negative relationship (interaction 20-22). However, it is the diversity and productivity of the Kenai's resource units that supports such a diverse set of resource users. One interviewee emphasized the importance of this relationship by saying, "You can't overstate that the Kenai is the backbone of this entire peninsula. Regardless of what fishery or business sector you are in, if this river is struggling the whole community is struggling." Resource users have a direct, negative relationship with parts of the resource system (e.g., sport fishers causing streambank erosion which affects rearing habitat) (interactions 23-24). Lastly, resource users help create regulations through the Alaska Board of Fish and resource users fund the Alaska Department of Fish and Game through licenses and permits (interactions 17-19). Ultimately, resource users have great potential to negatively affect the resource system and resource units, as we have seen many times throughout history. It is the governance system, supported by resource users, that acts as a mediator between resource users and the other first level variables in the model to help sustain the "backbone" of the Kenai Peninsula.

Each group of resource users have unique characteristics. For example, the areas they fish, the tactics they use, and their motivations all vary to some degree, and all contribute quite substantially to the culture and economic well-being of the region. They also contribute to the harvest of salmon. On average, the annual harvest rate for the three groups in the Upper Cook Inlet is as follows: commercial fishers harvest approximately 2.9 million salmon, sport fishers harvest 500K salmon, and personal use harvest 500K salmon (Martson, 2021; Schoen et al., 2019). We provide a detailed description of each group of resource users in the Supplementary Material.

4.3.2 Conflict.

With so many resource users all vying for a limited supply of resource units, there can often be conflict, and salmon fisheries, including the Kenai, are no exception. However, these conflicts go far beyond simple allocation issues. The term ‘Salmon Wars’ has been used for decades to describe the conflicts surrounding salmon fisheries. These conflicts are multifaceted, long-standing, complex, and often they are seemingly impossible to manage. Much has been written about Salmon Wars (see Brown, 2005), including works focused specifically on the Kenai Fishery (see Harrison and Loring, 2014; Loring, 2016). The perspectives of native peoples are also being recognized and discussed more, such as Norgaard’s (2019) work detailing the perspective of the Karuk Tribe in California. These resources provide detailed accounts of the conflicts, their histories, and frameworks to address them. Therefore, we will not repeat those details here. We do want to emphasize, however, that the conflict around salmon on the Kenai is present and ongoing. Each interviewee discussed it and provided their perspective. Two issues of conflict amongst resource users warrant further discussion here: paired restrictions and the Kenaitze.

4.3.3 Paired Restrictions.

Paired restrictions are an innovative regulatory measure that has been implemented in the Upper Cook Inlet to help reduce “perceived inequality” among resource users, as one interviewee said, “The way we have solved [the perceived inequality] in Cook Inlet is pairing our restrictions so everybody suffers together.” This interviewee went on to describe how Bristol Bay is currently experiencing growing conflict between resource users by saying,

> Right now, the sport fishers are restricted to [harvesting] two Chinook, [and the sport fishery] might go to catch-and-release soon on Chinook. The commercial fleet is not restricted at all. They are out there fishing as hard as they can. But the sport fishery is not causing the volume of mortality that the commercial fishery can. That’s the challenge; we have to figure out ways to deal with this. Right now, the sportfishing side feels like they are shouldering all the burden of conservation, and if everyone does not feel like they are shouldering it, then animosity grows.

By paring restrictions, all resource users are more equally “shouldering the work of conservation.” Multiple interviewees carefully made a point to emphasize this phrase. Currently, restrictions (interactions 27-29) are set up in phases, starting with light restrictions that can become more aggressive if conditions unfold unfavorably as the season progresses. The overall idea is that if restrictions are put into place, all resource users will be restricted, and as restrictions increase, each user group is affected equally through specific regulations intended to reduce their impact on the fishery—primarily Chinook. As all groups perceive they are “shouldering the work of conservation” equally, potential disputes may be mitigated. However, if the commercial fishery is continually restricted access from harvesting the plentiful Sockeye to conserve Chinook, support for Chinook conservation may waver.

4.3.4 The Kenaitze.

The second issue related to conflict and access worth emphasizing is the perspective of the Kenaitze Tribe because it is commonly neglected. For much of the 20th century to today, the Kenaitze have faced the lion's share of inequity. As one interviewee stated, much of this is rooted in greed: "There's this 'me' and 'my' and 'you are getting more' and 'you are doing this.'" In reflecting about the trouble the tribe has had gaining access to the fishery, and the trouble the tribe still faces, they said "Things have changed so much, but they remain the same—the people remain the same." As the interviewee described, as the commercial fishery opened in the 1920s, this gave the men jobs. The women would run a few nets set on the Kenai River near the ocean during the summer. This interviewee said, when you needed food,

> You just went down [to the nets] and got your salmon to eat. If you had too many and you didn't need them, your neighbor would take them. That's all that was. It was a necessary thing, and you share it. Makes good sense, right? Then along came the word 'subsistence.'

As the interviewee describes, the word "subsistence" brought along with it "plain prejudice and racism. It brought a lot of things into here which we have not gotten over today. I have to say that. Because it's true." Shortly after the commercial fishery opened, the fishery was depleted, which brought new regulations that restricted the Kenaitze from the fishery. One interviewee noted,

> In 1935, we had no fish because it had been fished out. Every bay, nook, and cranny. I remember the people, the women seemed so sad. Here comes the winter, what are we supposed to do? [Because of this] people started talking conservation. Good! [However,] along with the subsistence stuff, we couldn't put our nets in the river for food anymore.

One reason for this was that grocery stores had been built in the area, so "some people here said that we don't need subsistence because we can go to the store and buy our fish. They looked upon subsistence as welfare, like we were too poor [to buy food]…" However, to the Kenaitze, there was a lot more value to the nets than food:

> It's not just about supplying us with salmon to eat, it's about teaching. In 1973 we talked about getting a net, because I was teaching our children at the time how to set a net. Also, you talk about sharing and caring and knowing about the ecology of your land, fine, the best thing to do is to teach. You can teach a lot down here right where the net is now. It was just a matter of teaching our children to share and care about other people, because that is what we did. The goal was to teach values.

As the Kenaitze were trying to regain the ability to set a net, the goalpost was constantly moved. Finally, they found a loophole in the law, as the interviewee explains, "instead of calling it a subsistence fishery, we called it an educational fishery. And it made the difference [for us to get access]." When it came time to get the permit, the interviewee said, "the commissioner kept saying, 'oh, I forgot. I forgot.' He was stalling." Once the permit was signed, and the tribe started fishing, the interviewee said,

> When we put our net out in the river you would have thought that we were going to kill the world. The name calling came out when we got the net, and I was flabbergasted. People we knew personally [called us names]. Usually when there were no men around. We would be fishing, and if it was all women, it was really awful. There was no reason for it, but it was there.

The interviewee also described that most of the animosity they received came from the sportfishing community, saying,

> The commercial fishermen were very good with us. They supported us with nets because they knew what we were doing was okay. Sportfishermen thought we were going to take all the fish away from them. I don't know how we were going to do that, but they believed it. To some extent, I think some of that feeling is still here.

This is just a brief overview of the Kenaitze's issues in trying to gain access to the Kenai fishery, and their conflict with other resource users. Many of the points described here are echoed in Norgaard (2019) and Brown (2005). We present the Kenaitze's perspective to highlight that similar institutional systems and strategies have been used throughout salmon fisheries to restrict native people's access to them. With regards to the allocation of resource units in salmon fisheries native people are often the group that lose the most.

4.4 Governance System

The governance system of the Kenai was the most difficult for respondents to operationalize. There are multiple reasons for this, including that the Kenai fishery is managed by a conglomerate of local, state, and federal entities—all with distinct, but sometimes overlapping responsibilities that affect salmon and the fishery in various ways. Although there are overlaps, the general structure of the Kenai fishery's governance system is split between the Alaska Department of Fish and Game, which has the primary responsibility for managing and monitoring the resource units, and the federal agencies, such as the Forest Service and the Fish and Wildlife Service, that primarily manage the land and habitat.

In this fishery, interviewees identified the three primary goals of the governance system as: 1) maintaining sustainable fish populations (i.e., resource units); 2) providing and protecting quality habitat (i.e., resource system); and 3) providing quality fishing opportunities (i.e., resource users). These goals illustrate the governance system's role as the mediator of the system. The governance system monitors, protects, and invests in habitat (interactions 31-35). It monitors (interactions 15-16) and invests in the resource units, and it also regulates their harvest (interactions 27-29). It also manages resource users to reduce conflict, create equitable opportunities, and reduce the impacts resource users have on resource units and the resource system (interactions 27-29).

As the mediator between the resource system, resource units, and resource users, the governance system has two basic functions: assessment and management. The governance system *assesses* the resource system (e.g., rearing habitat, water quality, etc.; interactions 31-35), resource units (e.g., escapement; interactions 15-16), and resource users (e.g., harvest rates, catch-per-unit effort; interactions 27-29). These assessments are used to evaluate the effectiveness of the governance system in achieving its overarching goals. The *management* function is used to adjust interactions in the social-ecological system and steer it towards overall goals. The types of management functions interviewees identified are time, area, limits, methods and means, habitat restoration, enforcement, and education.

4.4.1 Types of Management Functions.

The governance system regulates when resource users can fish, where they can fish, how much they can harvest, and the methods and means they use to harvest (interactions 27-29). The practice of adjusting each of these levers is a delicate balance between providing opportunities for resource users and protecting the resource units. The primary reason for this is because the resource units—particularly salmon—can be quite unpredictable. Therefore, decisions intended to balance the harvestable surplus and sustainable escapement are made in real time (i.e., in-season), and getting this balance wrong results in highly unfavorable conditions for resource users and unsustainable escapements. The balance is crucial for long-term biological and economic sustainability of the Kenai.

The governance system also monitors habitat and invests in habitat restoration. For example, because of angler foot access, riverside developments, and boat wakes, rearing habitat on the Kenai River was in a degraded state in the 1990s. To address these issues, which were believed to be a reason for this stage in Chinook decline, efforts were focused on restoring riparian habitat through purchasing land that contained critical habitats, providing low-impact river access to anglers (i.e., light penetrating walkways), and creating a development plan to protect the watershed's function and integrity (Weiner, 1998; interaction 33). The Alaska Department of Fish and Game was a major player in these efforts.

To make sure different types of management functions are effective, the governance system also acts as the enforcer of regulations and the educator of resource users. In addition to standard law enforcement practices, the Alaska Division of Natural Resources has implemented an innovative educational program for guides on the Kenai. The Kenai River Guide Academy was proposed by the Kenai River Guide Association to help reduce conflict between users. One interviewee described the program,

> The Guide Academy is now required by regulation for all sport fishing guides on the Kenai River. There is no other place in Alaska that requires fishing guides to have successfully completed this 40-hour training. Ethics are a big component of the training, but there is also a natural and cultural history component. The classes are taught by park rangers, the wildlife refuge, Alaska Fish and Game, Coast Guard, and the university…What you have seen is the reduction in the number of citations that are issued to fishing guides. We can track those. I'm just going off the top of my head [but there used to be] a dozen to 20 citations a year…last year we only had three. If a fishing guide receives a citation, they can be suspended from one day to 30 days.

The paired restrictions noted above are another innovative type of management function taken on the Kenai. As restrictions increase for one sector, they also increase for the other. This helps create equity, so animosity does not build, and all parties "shoulder the work of conservation" together.

4.4.2 Assessment tools.

Within assessment, there are a host of measurable indicators that inform how well the governance system is doing in achieving its overarching goals. There are two broad areas of assessment; one is focused on the resource units and the other is focused on the resource users.

For resource units, specifically anadromous fish, the governance system estimates total run, in-river run, and escapement (interaction 16). The total run is composed of all the mature anadromous fish returning to the Kenai to spawn. As fish are returning to spawn, they are intercepted by commercial fishers in the ocean and personal use fishers at the mouth of the river. The in-river run is the total run minus commercial and personal use harvest. Once in the river, anadromous fish are harvested by sportfishers. Lastly, there is escapement, which is the remaining fish that were not harvested. The Alaska Department of Fish and Game has escapement goals which are set to ensure enough fish escape the fishery to spawn. Reaching escapement goals are important for resource unit sustainability (interaction 30).

In addition to assessing the resource units, the governance system also assesses resource users (interactions 27-29). As one interviewee described it, "We do not just try to understand how many salmon there are and what the fish are doing, there is also the human aspect that we look at—how many people are out there, how successful are they being—all of those things tie into what [management does].” The primary way the governance system assesses resource users is through catch-per-unit effort, which is how many fish are caught given a specified amount of effort. Catch-per-unit effort provides information about fish abundance and the quality of the fishing experience.

One major challenge is funding the assessment efforts. If funding is short, and assessment is not done, then these missing data cannot inform population trends. In addition, if a return is low but there is no assessment to identify that, then no restrictions are put into place to help reach escapement goals. When deciding what fish/fishery to assess, one interviewee said,

> It really comes down to how important the fishery is determined to be. Ultimately, we would love to have assessment on every whitefish stock in [the region], but we don't have those kinds of resources. So, clearly the effort and funding we put into a resource is directly related to how important it is to the people of this state of Alaska.

Because of the Kenai’s importance, a lot of resources are invested into assessing the fishery, and the results of that assessment are extrapolated to other, nearby fisheries (interaction 25). When runs are low on the Kenai, restrictions are applied broadly throughout the Cook Inlet, as one interviewee explains,

> The Kenai is a very important fishery, so it gets a lot of resources regarding what we try to do in-season. Because we're able to do that in-season assessment, the Board of Fish is then able to use that data to tie it to other fisheries. Now, our in-season assessment becomes even more important because actions we take affect other fisheries; it affects the set netters, it affects the drift netters, and it affects the marine fisherman all the way down in the lower Cook Inlet. Actions taken based on the Chinook data [gathered on the Kenai] affect a lot of different user groups.

This quote also emphasizes the impact of low Chinook returns, and how the commercial fishery—which is primarily focused on Sockeye—is affected by regulations intended to protect Chinook. This quote also states the authority of the Alaska Board of Fish, which is a seven- member board that is charged with assessing fisheries and making regulations to help the governance system achieve its goals. The Board of Fish does this by setting seasons, bag limits, methods and means for the state's subsistence, commercial, sport, guided sport, and personal use fisheries (interaction 26). The Board of Fish also makes policy and gives direction to the Alaska Department of Fish and Game (ADF&Gb, N.D.). Anyone can submit proposals for considerations about changes they would like to see in the state's fisheries (interactions 17-19). To summarize this process, and the role of the Alaska Board of Fish, one interviewee said,

> The board of fish makes the regulations, and the Fish and Game gives them the science that they need to pass sustainable regulations. Then the public can go in and say, "hey, I see something." Do they listen? Well, maybe. Sometimes they do. We have created management plans and done all kinds of stuff. That is the management of Alaska.

Ultimately, the governance system has the overarching goal of providing resource users equitable access to a sustainably managed fishery. The main ways this is achieved is through management tools and assessment. Resource users support the governance system through submitting proposals and funding. Then in turn, the governance system oversees the management of the resource system, resource units, and the resource users. Given the unpredictability and complexities around salmon, the governance system is walking a thin and challenging line between user access and sustainability. One of the most challenging aspects of this is that the most imposing restrictions are put in place because of low Chinook returns, which is not the target of many resource users.

However, because their methods are indiscriminate and have the potential to heavily impact Chinook escapement, they are restricted. The three ways out of this situation are: 1) forfeit efforts to conserve Chinook; 2) allow the commercial fishery to use more selective gear (i.e., fish traps); or 3) Chinook abundance returns to historic levels. Given the current cultural, ecological, and legal constraints, there do not seem to be any 'win-win' scenarios (Redpath et al., 2013).

5. Discussion

Above we have identified the components and interactions that depict the basic structure and function of the Kenai salmon fishery. In the discussion, we would like to illustrate how this model, and the model building process can be utilized to assess a social-ecological system. In Chapter IV, we use this model to map how fire can impact a fishery and identify vulnerabilities that may result in long-term impacts, which is a very focused exploration on one kind of disturbance. Here, we discuss the particular variables and interactions within the Kenai fishery that promote and impede the system's overall sustainability.

To do this, we use the 10 variables (e.g., resource system size) identified by Ostrom (2009) that influence the likelihood of whether a system has, or may, self-organize to become sustainable. In this evaluation, we find that the same variables that impede a system from self-organizing continue to influence a system's sustainability far after a system has self-organized. Therefore, these variables not only influence self-organization, they influence the success of a system in achieving the overall goal of sustainability. We list each of the variables and their influence (i.e., positive or negative) on the Kenai fishery's sustainability below, along with a description of how that variable influences a system generally, and how it influences the Kenai fishery specifically.

5.1 Resource System

5.1.1 Resource system size (Negative).

The size of the resource system has a curvilinear relationship with sustainability. Meaning, medium sized resource systems are much more likely to self-organize than small or large resource systems. Moderate sized coastal zones, rivers, and lakes are the most likely to self-organize (Wilson, Yan and Wilson, 2007), as opposed to large ocean fisheries (Berkes et al., 2006). Large resource systems like the Kenai fishery have high costs in defining boundaries, monitoring, and knowledge generation; these factors negatively affect the ability of the system to be managed in a sustainable way. As interviewees described in the modeling process, the Kenai fishery's resource system is large and diverse, spanning thousands of miles across vastly different habitats (i.e., mountain streams to open oceans). Any unfavorable condition in this long chain of habitats can act as a bottleneck for salmon productivity. Much of the inland portion of salmon habitat is understood, although there are still questions, but the ocean is still considered a "black box" by many. Monitoring salmon within this vast area is difficult and expensive, and there is still a lot we do not know about salmon when they are in the ocean. Because the Kenai and other salmon fisheries are so important, many resources have been devoted to defining boundaries, monitoring, and knowledge generation. However, despite these efforts, the size of the Kenai Fishery's resource system still provides many challenges.

5.1.2 Resource system productivity (Positive).

The productivity of the resource system also exhibits a curvilinear relationship. If resources are already depleted or perceived to be abundant, users will not see a need to manage them for the future. However, if the system is productive but users perceive scarcity, then they will be more likely to take action towards sustainability (Wade, 1989). The Kenai has had many instances of scarcity, starting in the 1930s when the fishery was first depleted by commercial fishers. This first indication of scarcity started people "talking conservation", leading to new laws to manage the system. Even though the Kenai is a highly productive system, it is utilized by a large and diverse set of resource users, therefore making the allocation of the Kenai's resource units scarce. Because this resource system is highly valued, productive, and heavily utilized (resulting in scarcity), a great deal of effort is devoted to monitoring and managing the fishery. Right now, alarmingly low Chinook abundance is driving the most innovative conservation, regulatory, and monitoring efforts.

5.1.3 Resource system predictability (Negative).

The dynamics of social-ecological system need to be sufficiently predictable so users can estimate the outcomes of regulatory measures. Forests are relatively predictable, but some fisheries approach mathematical chaos and, as such, are particularly challenging to model and manage (Acheson, Wilson, and Steneck, 1998). We heard this exact comparison between forests and salmon from one interviewee. Salmon are notoriously difficult to predict because they occupy such large areas and are acted upon by so many variables—natural and human. Without the ability to predict how the resource system will behave and how many resource units it will produce, in-season management becomes the only tool resource managers have. Although it is good to have this tool, it creates a lot of unpredictability for resource users. If salmon returns are low, large restrictions can be implemented in a very short amount of time that can have a large effect on a fisher's ability to access and profit from the fishery. This unpredictability creates anxiety, conflict, and uncertainty.

5.2 Resource Units

5.2.1 Resource unit mobility (Negative).

Highly mobile resource units act negatively toward self-organizing because they are more costly and difficult to monitor and manage relative to stationary resources (Schlager, Blomquist, and Tang, 1994). Salmon are incredibly migratory, and are arguably more difficult to monitor than birds or wildlife because they live in the water where we cannot directly observe them. To understand their migratory behaviors and monitor them with more accuracy, complex monitoring efforts are used to gather tissue samples that are genetically analyzed to determine their place of origin (Faunce, 2015; West and Dann, 2017). Additionally, environmental factors like changing ocean currents may change salmon migratory behaviors making them more vulnerable to other risks, such as predation and/or "foreign fleets or big ocean fisheries," as one respondent described.

5.3 Resource Users

5.3.1 Number of resource users (Negative).

Transaction costs increase as the number of users increases. Organizing diverse users to create sustainable management efforts is very difficult (Baland and Platteau, 2000; Wade, 1989). A large group of resource users can be useful in monitoring the resource system, but the relationship between users needs to be collaborative, as opposed to adversarial. There are many diverse resource users who rely on the Kenai fishery. As described above, these users differ in many ways, and these differences, along with resource unit scarcity, have resulted in conflict. Not all conflict is bad, and the conflict on the Kenai has resulted in innovative approaches to managing the resource (e.g., paired restrictions). However, because so many people rely on the fishery, and harvest salmon at nearly all points in their return migration, it takes a lot of effort to monitor each user's harvest. In addition, it is difficult for users to agree upon regulations that may put them at a disadvantage to another resource user, even if the overall purpose is to increase the chances of achieving sustainability. Low Chinook abundance is challenging because it affects resource users differently. For example, even though the set net fishery is primarily targeting sockeye, which are currently quite abundant, the set netters can be heavily restricted to reduce their impact on Chinook. Paired restrictions are a way to increase equity among users, as all users are "shouldering the work of conservation" together. However, if set netters feel they are being disproportionately restricted from the fishery to conserve Chinook, their willingness to "shoulder the burden" may waver. More selective commercial fishing gear may be a way to address this issue, but there are many challenges that come with this as well.

5.3.2 Leadership (Positive).

Self-organization is more likely when some users have entrepreneurial skills and are respected as local leaders because of prior organization for other purposes (Baland and Platteau, 2000; Wade, 1989). There is already a strong management system for the Kenai fishery. The Alaska Board of Fish evaluates information and creates regulations while the Alaska Department of Fish and Game monitors and directly manages the fishery. Without this strong system of management, that in many ways succeeds in its mission, the Kenai may not be what it is today. The ability of resource users to overexploit the fishery was present in the 1930s, but the Kenai's current high productivity is a testament to management efforts. In the current governance system, each user group needs to advocate for themselves to the Board of Fish. Some organizations are highly organized and have a clear agenda which they advocate for, like much of the commercial fishing sector. Others, like much of the sportfishing sector, are not as organized and do not have as many resources devoted to organizing their constituency and advocating for their positions.

5.3.3 Norms and social capital (Negative).

Resource users who share moral and ethical standards regarding how to behave in groups, and thus have norms or reciprocity and sufficient trust in one another to keep agreements, will face lower transaction costs (Baland and Platteau, 2000; Trwick, 2001; Ostrom, 2005). In the Kenai fishery, there are long standing divides and a great deal of mistrust between separate user groups (e.g., between commercial, personal, and sport fishers). Because of their diversity and the limited nature of the system's resource units, their relationship can be quite adversarial. As interviewees described, the conflict was more intense in the past than it is today, but it still persists. Given the differences between users, and the history of conflict, there are still elements of distrust and animosity. However, new regulatory approaches such as paired restrictions, among other things, have moved this in a positive direction.

5.3.4 Knowledge of the SES (Negative).

When resource users share a common knowledge of a social-ecological system, they perceive lower costs of organizing (Berkes and Folke, 1998). Conducting interviews with such a diverse set of people illuminated the fact people understand the Kenai fishery differently. Some have a very good understanding of the system as a whole—particularly those in charge of managing it. However, there are some strong differences in the way resource users perceive the functioning of the system. This is understandable because the system is incredibly complex. The best available science still cannot answer some of the common questions people have, like why Chinook abundance is declining. There are also perceived differences in how each of the resource users affects the system. For example, the term 'overescapement' was brought up as a point of contention between resource users. The basic idea of overescapement is that if too many fish escape the fishery and spawn, the fish will exhaust their resources which will lead to a population crash. This view is primarily held by commercial fishers, and they see it as their role to protect the fishery from overescapement to maintain the fishery's sustainability. Sportfishers obviously disagree, but they also benefit from more fish in the rivers because it improves their opportunities to catch them. Managers generally hold the view that overescapement is possible in some systems but is very unlikely in the Kenai. There is also a lot of finger-pointing among resource users as to whose fault it is that Chinook are declining. Many sport fishers say it is because of commercial fishers; commercial fishers say it is because of sportfishers, and on and on. The answer to why Chinook are declining is much more complicated, and although there are some obvious factors, there is still not a common consensus. Now researchers and others at the forefront of the issue are looking at how changing environmental conditions driven by climate change and the introduction of hatchery salmon in the ocean may be affecting wild populations of salmon. Many factors contribute, but there is still a lot that is unknown. Therefore, getting a diverse group of resource users to agree on a management direction to reverse the declining trend in Chinook abundance when there is no clear cause, is very difficult. Therefore, potentially harmful processes will continue until we have a better understanding of their impacts. It is also a possibility that the cause of Chinook decline is an exogenous variable, such as climate change, and therefore far out of the Kenai fishery's governance system's ability to address.

5.3.5 Perceived importance (Positive).

In successful cases of self-organization, resource users are ether dependent on the resource system for a substantial portion of their livelihoods or attach high value to the sustainability of the resource. If not, resource users may think the costs are not worth the effort (Ostrom et al., 2002; Berkes and Folke, 1998; Chhatre and Agrawal, 2008). There is great value in the Kenai fishery, with many resources being devoted to understanding it, monitoring it, and managing it. Despite this, Chinook are still declining. Even though

Chinook abundance is low, the rest of the fishery is in a good state. Other species are doing well, there is equitable access to the fishery, and the Kenai fishery generates a lot of economic activity. The reason so many resources are directed toward monitoring and managing the Kenai is because it is considered very important to "the people […] of Alaska." Efforts to manage the fishery sustainably are still very active, which can be largely attributed to the importance of the resource amongst resource users and those involved in the governance system. The importance of salmon fisheries is the driving force behind the massive efforts and resources devoted to restoring and managing them sustainably. However, it is also important to note that a large portion of funding for these efforts comes from fishing permits and licenses. Therefore, if resource users lose access to resource units, and revenue declines, then fewer funds will be available for future research, restoration, and monitoring.

5.4 Governance System

5.4.1 Collective-choice rule (Positive).

When resource users have full autonomy to craft and enforce some of their own rules, they face lower transaction costs as well as lower costs in defending a resource against the invasion of others (Berkes et al., 2006). Overall, the Kenai's governance system is within the realm of collective-choice rule. Anyone can submit proposals to the Alaska Board and Fish and advocate for their proposition. However, as interviewees described, the process can be highly political as the Board is comprised of seven members appointed by the governor of Alaska. Depending on what direction the current governor leans, members are appointed who will vote in one direction or another. We have no empirical evidence to support this, but it was a concern voiced by interviewees. Some interviewees also noted the commercial fishers are much more organized in terms of proposals and advocating for their positions. Overall, the opportunities for resource users to be involved and guide the management of the system is present withing the current governance system.

Overall, it is the large size and unpredictable nature of the resource system, combined with the mobility of the resource units that leads to the social issues that arise in management. Because the resource units inhabit such a large area, they are harvested by a broad collection of resource users. As such, there is a great deal of diversity among resource users, which contributes to the lack of commonalities between them, including how they understand the function of the social-ecological system and what management actions are deemed acceptable. The variability and uncertainty of the resource system also contributes to challenges. For example, although there are supported theories explaining the cause of low Chinook abundance (e.g., hatchery salmon, climate change, etc.), there is yet to be a definitive answer. As Singleton (2000) states, resource users and the governance system "must have sufficient information available to them to allow for the creation of effective management" (p.4). Therefore, the diversity in resource users, along with the uncertainty in clear management direction to deal with pressing issues (e.g., chinook abundance) creates conflict around how the system should be managed. Ultimately, it boils down to ecological complexity driving social complexity. These are the fundamental issues the Kenai fishery is faced with when trying to achieve sustainable management.

6. Conclusion

Despite many challenges, the current state of the Kenai fishery is quite good. It is a productive system that supports a diverse set of resource users, and its role as the “backbone” of the Kenai Peninsula cannot be overstated. It is the importance of the Kenai that explains why so many resources have been devoted to monitoring and managing it. In many ways, the governance system is succeeding in its overarching goals of maintaining sustainable fish populations, providing and protecting quality habitat, and providing quality fishing opportunities. However, despite its importance and the resources devoted to managing the fishery, the decline of Chinook salmon is a major concern threatening the sustainability of the system.

The reality is that the Kenai fishery may be in the middle of a regime shift from its past state to a highly resilient but less desirable social-ecological system. Specifically, we may be seeing species with more complex life cycles, like Chinook, be replaced by less desirable species with simpler life cycles, like pink salmon. One likely cause for this shift is density dependent dynamics in the ocean. If the cause for Chinook decline can be identified, it may already be too late to restore the historic abundance and size of Kenai Chinook (Biggs, Carpenter, and Brock, 2009). If climate change is the cause, recovery targets are likely unattainable because the change is occurring at a global scale, far outside the realm of addressable problems for the fishery alone (Allen et al., 2019). Allen et al. (2019) also provides two options for systems facing a regime shift. First, management can continue to expend resources to reducing the resilience of the current system state (i.e., low Chinook returns) to force the system back to a desired state—the current approach. The second approach is to determine whether to sink resources into the system at all (triage) given the level of resilience of the Kenai in its current, undesirable state.

Option one is resource intensive for the governance system, and the regulations that are put in place are costly for resource users. The costs imposed on resource users are causing them to seek opportunities elsewhere, increasing the pressure on other systems. For example, a set netter sold their Kenai permit and moved their business to Bristol Bay to escape the unpredictability of the Kenai fishery (personal communication). Now, the conflict and issues present on the Kenai are unfolding in Bristol Bay. Attempts to put out one fire are causing multiple fires across Alaska. The second option of triage could free up governance system resources to monitor and manage other systems, resulting in better monitoring for systems receiving additional use from displacement. However, this option poses enormous ethical questions and legal challenges. Neither option is ideal, but it is the reality the Kenai and many systems around the world face.

In conclusion, identifying the social and ecological components of the Kenai Fishery, and mapping the interactions between them, proved to be a useful tool in understanding the fishery and the current challenges it faces. Using Ostrom's (2009) social-ecological framework as the foundation for building fuzzy cognitive maps increased the scope and consistency of individual models, which arguably improved the quality of the aggregated model. We hope the method is used and built upon in future research to increase the consistency and accuracy of social-ecological system mapping. Although the aggregated model is by no means a perfect representation of the Kenai fishery, it is a helpful tool that can be used to build a consistent understanding of the system among stakeholders. Beyond being a tool for building consistency, the model can also be used as an evaluative tool, as we were able to demonstrate in our assessment in the discussion. In addition, this model can be used to explore the effects of disturbance events (see Chapter 4), set research agendas, and explore possible changes in management and how they may affect the system more broadly. Overall, we found this process yielded a good representation of the Kenai fishery and a deep understanding of its individual components as well as the interactions amongst them. The approach we have employed here shaped not only 'what we know,' but also 'how we know' about the complex social-ecological system that is the Kenai fishery. It is our hope that the social-ecological model as well as the knowledge generated through our approach can be used by resource managers, fishers, tribal leaders, and others to better understand the extent and complexity of the system and enable them to more effectively work together around a shared understanding.

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CHAPTER IV

ASSESSING THE POTENTIAL LONG-TERM SOCIAL AND ECOLOGICAL IMPACTS OF FIRE TO THE KENAI RIVER FISHERY (ALASKA, USA)

Abstract

In a rapidly changing environment where fires are becoming more frequent and severe, we need information and tools that can help us understand the broad scope of impacts fire can have in complex social-ecological systems. Taking a novel approach, we used a social-ecological model of the Kenai salmon fishery to conduct interviews and a systematic literature review to identify and detail how fire can, and has affected fisheries. We then distilled this broad scope of information into a set of conditions where fire may result in long-term impacts. Specifically, we identified that the most vulnerable fish populations are those that are isolated, lack quality habitat alternatives, and have low abundance. Applying this to the Kenai salmon fishery, we concluded that early-run Chinook salmon are the most vulnerable to fire, and if impacted, early-run Chinook have the greatest potential to severely impact the fishery more broadly through a chain of negative ecological and social interactions. Beyond fire, this model and approach can be used to assess a wide range of exogenous and endogenous forces being placed on fisheries, and in turn, potential outcomes, vulnerabilities, and opportunities associated with them.

1. Introduction

Fisheries around the world are influenced by many different social and ecological pressures. For example, a single fishery can fill multiple roles, acting as a commercial, recreational, and subsistence fishery all at the same time. The tension between these roles is increasing because demand for food and experiences is growing, and many fisheries are being utilized to, or over their capacity (Pauly and Zeller, 2017). In addition to the varied social demands on fisheries, intermittent large-scale wildfires can alter the productivity of a fishery and the stability of the broader social and ecological systems in which they are embedded. Additionally, the influence of intermittent large-scale wildfires is likely exacerbated by gradual exogenous stressors such as climate change. To shed light on these issues, we worked with stakeholders throughout the Kenai River Fishery in Alaska to collaboratively develop a model which displays the impacts of the Swan Lake Fire, which burned over 67,000 ha of forest land in 2019. Ultimately, the model serves as a generalizable tool that resource users and managers can use to explore the impacts of wildfire on the social and ecological components of fisheries.

Current projections suggest many areas across North America will experience more frequent and severe wildfires (Abatzoglou and Williams, 2016). Areas like the Kenai Peninsula have recently experienced an increased frequency in wildfires associated with warmer and dryer than average conditions (Sanford, Wang, and Kenward, 2015). In addition, the frequency of lightning—a common source of ignition—is increasing in northern latitudes as air temperatures warm (Holzworth et al., 2021). Megafires, fires which are notable for their magnitude and impacts, have also become increasingly common over the past several decades (Westerling et al., 2006; Williams, 2013). Most wildfires burn with a low to moderate severity, and ultimately have little impact on fish and fisheries. However, high severity burns—canopy fires that consume large amounts of surface fuel and leave soils resistant to infiltration—are becoming more frequent and can have dramatic effects on stream fishes (Burton, 2005, Gresswell, 1999).

There are numerous ecological consequences of fires on fisheries. In severely burned watersheds, there is an increased probability of post-fire flooding and debris flows (Brogan et al., 2019). These events can drastically reduce the presence of stream fishes by 70-100% (Burton, 2005; Rinne, 2004). A stream can rebound relatively quickly, sometimes providing better habitat than before the fire (Burton, 2005; Reeves et al., 1995; Sedell et al., 1990, Benda and Dunne, 1997, May and Gresswell, 2004). However, a stream's ability to rebound is contingent on the underlying ecological integrity of the fishery; if it was compromised before the fire there is a possibility that the stream will not be able to return to its pre-fire state (Rieman, Gresswell, & Rinne, 2012). Even though declines in productivity may be temporary, it would serve fisheries scientists and managers to know the full scope of social and ecological impacts of large-scale wildfires. Having a structured framework that can be used to identify impacts in a social-ecological system can also assist in the identification and exploration of policies and management practices which can be put into place to mitigate the impacts of large-scale wildfires.

Taking a social-ecological approach can be very useful in understanding how stressors and disturbances alter the components and stability of a particular social-ecological system. For example, the shift in annual stream runoff throughout the western United States is associated with warmer air temperature (Al-Chokhachy et al., 2017;

Isaak et al., 2012; Leppi et al., 2012; Rood et al., 2005; Stewart et al., 2004, 2005). Many of the studies investigating climate-driven shifts in stream conditions are usually focused on just one biophysical component of the system being affected (e.g., a particular fish species; Al-Chokhachy et al., 2021; Bell et al., 2021; Al-Chokhachy et al., 2017), and there have only been speculations about what the socioeconomic impacts of these shifts will be. Limited research has explored the larger context of these shifts using a social-ecological system approach (Lamborn and Smith, 2019). By taking a social-ecological systems approach, researchers can identify and map how biophysical changes affect multiple ecological, as well as social components within a system. A more holistic understanding is useful as it can provide insights into how the impacts of stressors and/or disturbances interact with one another, possibly in unforeseen and complex ways (Jones et al., 2020). This broader understanding can help us predict how disturbance events, such as large-scale wildfires, play-out and disrupt social-ecological system dynamics.

For heavily utilized fisheries, any reduction in productivity can cause large and far-reaching impacts. In Chapter III, we discussed how declines in Chinook (*Oncorhynchus tshawytscha*) salmon have affected the commercial and sportfishing industries. Restrictions put in place restrict commercial fishers, which in turn impact the businesses they support (i.e., fish processors). The sport fishing sector has also been affected because the resource can no longer support past use. Reductions in sport fishing opportunities also affects the local service industry. Similarly, fisheries in New England, USA, experienced declines in lobster abundance, which affected commercial fishers, and in turn all the parts of the economy they support (Steneck et al., 2011). When a fishery does experience scarcity, intense conflicts between resource users often result (Brown, 2005; Harrison and Loring, 2014; Loring, 2016). Therefore, identifying how a fire may lead to long-term reductions in a fishery's productivity may prevent economic losses and conflicts from occurring.

The ecological impacts from fire and post-fire flooding have been explored in the literature, but to our knowledge, how a fire can affect the broader social-ecological system of a fishery has not. Therefore, the focus of this research is to expand the current state of knowledge of these impacts by using a social-ecological systems approach. This approach facilitates a more holistic exploration into the impacts of climate change and disturbance events, such as wildfires. The three contributions of this research are as follows:

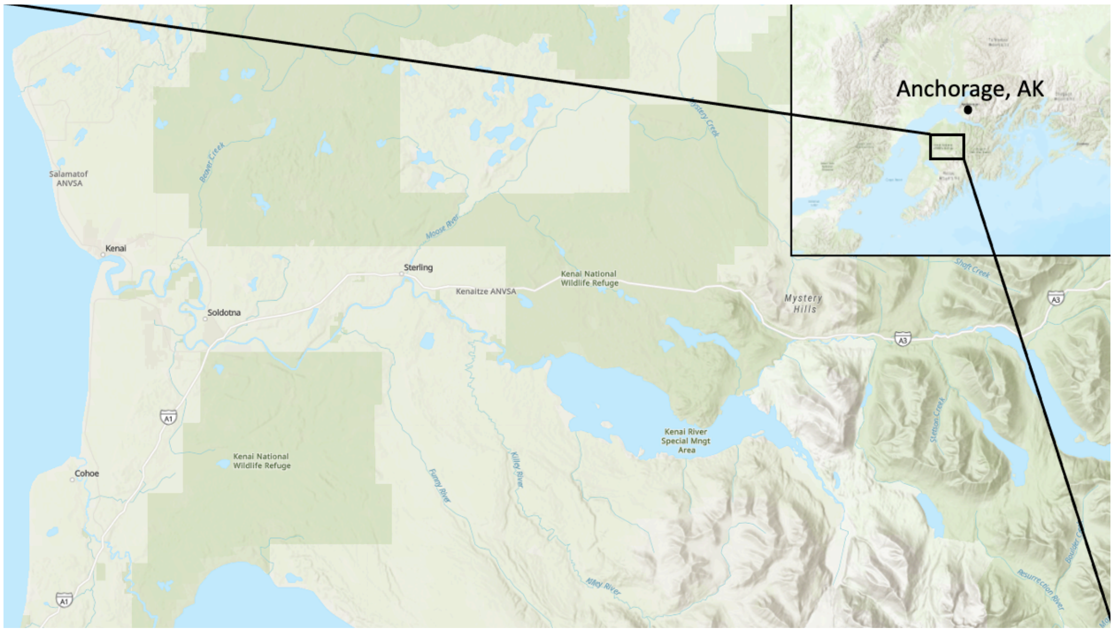
1) The collaborative development of a model with stakeholders which identifies the social and ecological impacts of a large-scale wildfire on a coastal fishery; and
2) The organization of knowledge and identification of knowledge gaps regarding the social and ecological effects of fire on a coastal fishery.

2. Study Area

The Kenai Peninsula in southcentral Alaska is comprised of a very diverse landscape. It contains alpine tundra, boreal forests, icefields, temperate rainforests, and wetlands, and it straddles two different climatic zones. The east side of the Kenai Peninsula is mountainous and receives a large amount of precipitation. These mountains, known as the Kenai Mountains, are covered with alpine tundra and glaciers, and the foothills near the ocean support a coastal temperate rainforest (O'Neel et al., 2015). The west side of the peninsula sits in the Kenai Mountain's rain shadow and is characterized

Figure 4.1.

Map of the Kenai River, Alaska



as a subarctic continental climate (Shulski and Wendler, 2007). These western lowlands are covered by boreal forests and extensive wetlands (Klein et al., 2005).

Glaciers descending from the Harding and Sargent icefields cover 11% of the Kenai River's 5,568 km^2 watershed (Dorava and Milner, 2000), and the runoff from these glaciers gives the river its turquoise blue color. The Kenai River originates from Kenai Lake in the Kenai Mountains and runs a total length of 182 km (118 mi). As it flows westward, it is met by three different kinds of tributaries—glacial, mountain, and lowland—and flows throughs the very large, and deep, Skilak Lake. Each of these features play an important role in the Kenai River ecosystem and contribute to the Kenai River's high productivity (Figure 1).

The Kenai, which is the most productive river in the region, supports commercial, personal use, and sport fisheries; each of which play important and diverse roles. For example, the commercial harvest of wild pacific salmon in the North Pacific Ocean is near all-time highs, and one-third of the salmon being harvested spawn in the Gulf of Alaska region, which includes the southern Alaska Peninsula, southcentral Alaska, and Southeast Alaska (Irvine and Fukuwaka, 2011; Irvine and Ruggerone, 2016). Historically, the Kenai River has produced approximately 35% of the salmon commercially harvested in the Cook Inlet basin, even though it occupies less than 6% of the basin's total area (Dorava and Milner, 2000). The Kenai River is also the most popular sportfishing destination in Alaska, receiving an average of 275,000 angler days per year (ADFG, N.D.); it provides exceptional angling opportunities for chinook (*Oncorhynchus tshawytscha*), coho (*Oncorhynchus kisutch*), sockeye (*Oncorhynchus nerka*), and rainbow trout (*Oncorhynchus mykiss*) (Begich et al., 2013). Residents and non-residents seeking these sportfishing opportunities contribute greatly to the region's economy, spending money on guides, gear, lodging, food, etc. The personal use fishery, which is only available to Alaskan residents, provides them an opportunity to harvest their annual subsistence allotment using more efficient means, like dip nets. In total, these three groups harvest approximately 3.5 to 6 million salmon from the Upper Cook Inlet each year. Commercial fishers harvest the largest proportion of the total catch, which fluctuates around 2.5 to 5 million fish per year—the vast majority of which are sockeye. Recreational anglers and personal use fishers harvest approximately 500,000 fish each, totaling around 1 million fish annually, with sockeye again being most of the catch (Schoen et al., 2017).

Like many regions, the Kenai Peninsula has been experiencing rapid environmental change, including warmer than average temperatures, increased lightning frequency, spruce beetle kills, and an increase in fire risk, frequency, and severity (Berg et al., 2006; Hess et al., 2019; Holzworth et al., 2021; Sanford, Wang, and Kenward, 2015; Schoen et al., 2017). Historically however, fire on the Kenai Peninsula has been quite rare, with a fire interval between 400-600 years (Berg and Anderson, 2006). In contrast, over the last 80 years the area around the Kenai River has experienced four large fires: the 1947 Kenai Fire (128,726 ha), the 1969 Swanson River Fire (34,522 ha), 2014 Funny River Fire (79,565 ha), and the 2019 Swan Lake Fire (67,000 ha).

3. Methods

3.1 Process Overview

We took a mixed methods approach in our investigation into how fire can affect the Kenai. using A mixture of methods can greatly improves the depth, scope, and applicability of research outcomes (e.g., Johnson and Onwuegbuzie, 2004). Our approach can be broken down into four parts. First, we began by developing a social-ecological systems model that represents the components and interactions of a coastal fishery in the northern Pacific. The model was developed collaboratively with key stakeholders throughout the fishery, and is grounded in Ostrom's general framework for analyzing sustainability in social-ecological systems (2007; 2009) (see Chapter III). Second, we collected interview data focused on how the Swan Lake Fire affected the Kenai River watershed and fishery. Again, this was done with key stakeholders throughout the fishery (full details below). Third, using our social-ecological framework as a guide, we conducted an extensive literature review focused on the relationships and dynamics between fire and fisheries. Coupling interview data with published data and knowledge from the scientific literature allows for a more robust representation of the dynamic influence of fire on the social and ecological components of the fishery. Finally, we use the interview data and existing literature to identify potential long-term impacts of fire on the Kenai fishery.

3.2 Social-Ecological Systems Model

The base model used to explore the impacts of fire was developed by taking a novel approach to social-ecological systems mapping (Chapter III). The core of Ostrom's general framework is a set of four variables: 1) resource system; 2) resource units; 3) governance system; and 4) resource users. All social-ecological systems have these four 'first-level' variables. However, Ostrom (2007) describes these first-level variables as 'decomposable,' meaning they can be broken down into many second-level variables that represent the structure of a particular system and the research question being addressed. The second level-variables in the model were identified through interviews with key stakeholders. Our interviews were structured around a fuzzy cognitive mapping process (Kosko,1986). Gray et al. (2013) describe fuzzy cognitive maps as a "complex form of data collection where study participants are asked to develop qualitative static models which are translated into quantitative dynamic models" (p. 967). Fuzzy cognitive maps are useful in helping us understand complex social-ecological systems because they: 1) can be used to map the structure of a social-ecological system; 2) allow for knowledge sharing between stakeholders; 3) analyze social-ecological system functions through scenarios; and 4) can be used to evaluate how changes in variables may move the social-ecological system toward or away from overall goals (Gray et al., 2015). The software Mental Modeler (Gray et al., 2013) was used to develop the social-ecological systems model. For a complete overview of how the social-ecological systems model was developed, refer to Chapter III.

3.3 Interview Data

Interview data was collected from key stakeholders in the Kenai River region. The data collection occurred in two steps. The first step was to collaboratively build social-ecological systems models that represented the Kenai River fishery with stakeholders. After each individual model was complete, we transitioned into a conversation about the impacts of fire. Having the base model complete, with all of its components and interactions, allowed us to have focused conversations about how fire affects specific aspects of the model.

For the interviews, we sought knowledgeable and experienced stakeholders who had expertise in diverse fields. The types of people we interviewed included federal resource managers, state resource managers, advocates, people from non-profits, tribal members, and business owners (from commercial and sport fishing backgrounds). We specifically sought people who had extensive experience within the Kenai River Watershed. We utilized a chain-referral sampling method to identify additional interviewees at the end of interviews.

In the initial effort we interviewed ten people. The average time it took to complete a fuzzy cognitive map was 2 hours and 9 minutes (the minimum interview time was 50 minutes and the maximum was 4 hours and 12 minutes). Since many people have a shared understanding of a system, the number of new concepts introduced quickly diminishes as the number of interviews increases. Looking at previous studies, Özesmi and Özesmi (2004) were able to show the accumulation of new variables declined drastically after approximately ten mapping exercises. We found this to hold true and concluded the first round of data collection after ten interviews were completed.

Individual models were then combined into one aggregated model representing the Kenai fishery. The process we used to combine individual models can be found in Chapter III.

3.4 Model Validation

After one aggregated model representing the social and ecological components of the Kenai fishery was complete, we conducted a model validation process through a second round a data collection. This was done by conducting interviews with prior interviewees, in addition to new stakeholders. This second phase of data collection consisted of presenting a printed version of the aggregated model to interviewees, and then asking them to critique the model. We provided markers for the interviewees and encouraged them to write on the printouts. Each interview was recorded so we could refer to conversations if needed. We interviewed 11 people during the validation process. Interviews ranged from one hour to over three hours, and the average interview lasted approximately 90 minutes.

3.5 Interview Data

After our discussions on the model's overall accuracy, we transitioned into a conversation about how fire has, and can, affect the fishery. Using the model as a guide, we walked through each component of the model and discuss how the Swan Lake Fire affected the fishery. We also discussed potential impacts from future fires, and how interviewees are thinking about fire in a rapidly changing environment. We present the themes from these conversations in the results.

3.6 Model-Guided Literature Review

In addition to the interview data, we used the model to guide a literature review focused on how fire affects each component of a fishery. There were three goals for the literature review. First, we wanted to increase the quality and generalizability of our model by exploring the literature to validate and add to the information gathered in the model building and interview process. Second, we wanted to provide a methodical review of information pertaining to the effects of fire on a fishery. And third, we wanted to use the interview data and literature review to identify scenarios where fire could potentially create long-term impacts to a fishery.

4. Results

The results are broken into four sections. First, we provide a brief overview of the model representing the Kenai fishery, and the specific components of the model which are affected by fire. More information about the model and its development can be found in Chapter III. Second, we present the results of our interviews with stakeholders about the effects of the Swan Lake Fire. The third section contains the model-guided literature review. This literature review synthesizes available information on how fire can affect the individual components of a fishery. In the fourth and final section, we illustrate how our model can be used to assess the potential social and ecological impacts of a fire to the Kenai fishery.

4.1 The Kenai as a social-ecological system

The result of the model building and validation process is a set of second-level variables that are nested withing Ostrom's (2007; 2009) framework; it also yielded a web of interactions between the second level variables. The aggregated map is shown in Figure 2. The overall flow of the system is as follows. First, the resource system—blue second level variables—is the foundation of the fishery. It is composed of a host of second level variables which sustain the ecological integrity of the ecosystem. Interviewees identified passage, spawning habitat, rearing habitat, water quality, and ocean conditions as being important components of the resource system.

The resource system then supports the resource units—orange second-level variables—which are classified into in-river fish and anadromous fish. Both in-river and anadromous fish are important to the fishery but play very different roles. For example, in-river fish are primarily utilized by the sport fishery, and mostly contribute to the service industry. The anadromous fish are utilized by all resource users and are the primary focus of the commercial and personal use fishers.

The resource units then support the resource users—yellow second-level variables—which are broken into sport, commercial, and personal use fishers. The resource users generally have a negative impact on in-river and anadromous fish through harvest and catch-and-release mortality. Some components of the resource system—such as streambanks and water quality—are also impacted by resource users through trampling, boat wakes, and boat engine exhaust.

The governance system—green second-level variables—affects and is affected by all other parts of the model. In the Kenai fishery, interviewees identified the three primary goals of the governance system as: 1) maintaining sustainable fish populations (i.e., resource units); 2) providing and protecting quality habitat (i.e., resource system); and 3) providing quality fishing opportunities (i.e., resource users). These goals illustrate the governance system's role as the mediator of the system. The governance system protects, monitors, and rehabilitates habitat. The governance system monitors resource units, produces resource units through hatchery production, and it regulates resource unit harvest. The governance system also manages resource users to reduce conflict, create equitable opportunities, and reduce the impacts resource users have on resource units and the resource system.

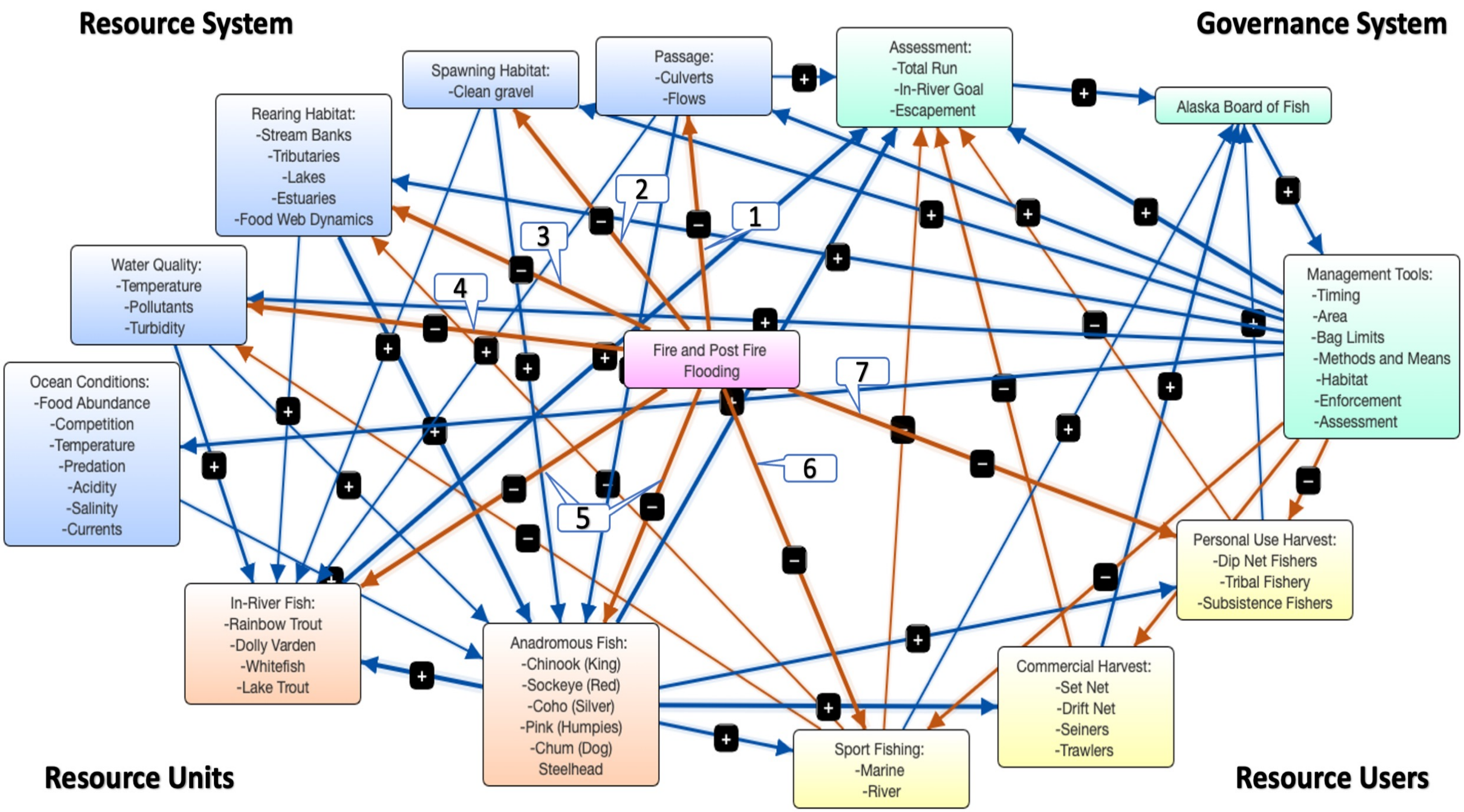
4.2 The impacts of fire on the Kenai fishery: Interview data

We asked interviewees to identify which second-level variables were affected by the Swan Lake Fire in 2019. Interviewees discussed two distinct, but highly related impacts. First, there are the direct impacts from fire, such as burning overground cover, restricting access because of safety concerns, and threatening or destroying infrastructure. The second impact is post-fire flooding, which for a fishery, is often the more detrimental impact. We combined fire and post-fire flooding in the model but describe the specific effects in the text. In addition to the impacts listed in the interviews, we also searched the literature for other possible impacts from fire. Much has been published about the specific impacts fire has on components within the resource system and on the resource units themselves. However, interviewees described in detail how the fire affected personal use and sport fishers by limiting access, but this was not discussed in the literature. Therefore, the full scope of impacts fire can have on a fishery are presented in Figure 2., which is the most comprehensive representation to date.

Figure 2 illustrates the ways a fire and post-fire flooding can impact a fishery. Within the resource system, fire and post-fire flooding can affect passage (interaction 1), spawning habitat (interaction 2), rearing habitat (interaction 3), and water quality (interaction 4). Fire and post fire flooding can directly impact fish populations, the resource units (interaction 5). Lastly, fire can directly affect personal use fishers and sport fishers (interactions 6 and 7, respectively). There is the possibility that fire may affect commercial fishers by threatening or destroying infrastructure and operations on land, but since commercial fishing takes place on the ocean, it is largely spared these impacts.

Figure 4.2.

The Seven Fishery Components Affected by Fire



4.2.1 Resource system impacts (interactions 1 – 4).

Even though the Kenai experienced a large fire with many areas of intense burning in 2019, the resource system was spared many potential negative effects. One interviewee explained very specific concerns he and his colleagues had, saying,

> We were worried about the usual things such as increased sedimentation in the river and tributary streams. We were also worried about increased erosion and increased flows. In some boreal systems, there are heavy metals released that could be detrimental. There were concerns, but we certainly didn't see it in any cursory looks.

Interviewees provided three primary reasons why the Kenai fishery's resource system was not impacted by the 2019 Swan Lake Fire. First, the years that proceeded the fire were dry, so there was not a lot of precipitation to cause post-fire flooding. One interviewee described this by saying,

> [It] has to do with the fact that 2019 and 2020 were as dry as they were. We didn't see any [impacts], most likely, because we did not get enough precipitation to cause any seasonal flooding, so I think the effects were mitigated.

Because the years proceeding the fire were dry, vegetation had a chance to stabilize soils before heavy precipitation could wash them away. Now, as one interviewee explained, "vegetation has grown into the fire area, so I don't think we will see that large washout of ash, even with this summer and as much precipitation as we have received—on the ecological effects, I think we're fine."

Second, most riparian areas were not burned which created a buffer between the burned areas and streams. One interviewee emphasized this point by saying,

> In general, along the stream banks, we did not lose enough structure to bring any concerns to my mind to the riparian habitat… The effects of the fire [to the fishery], on a hole, are minimal from everything I have observed.

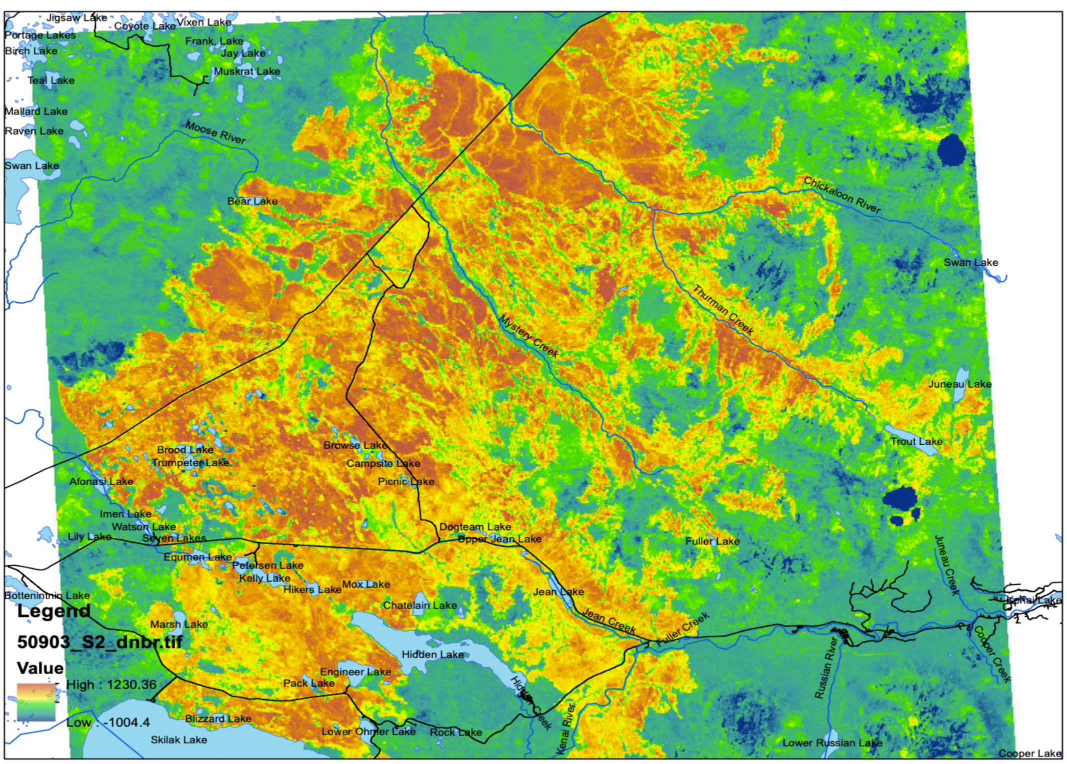
Lastly, the Swan Lake Fire did not burn a large portion of land adjacent to the Kenai or its main tributaries—most of the burn occurred north of the Kenai River watershed (Figure 3). An even finer point is that the fire did not burn any areas of high concern—like critical spawning habitat. One interviewee made this point by saying,

> The fire area did not incorporate any of our major spawning areas and tributaries like the Killey River, it was on the other side. The headwaters of the Moose were involved, and I think Jean lake and Crescent, [but overall the] impacts to the ecological and biological [components] were minimal.

As interviewees explained, because of a host of factors, the resource system of the Kenai Fishery was largely unaffected by the Swan Lake Fire. Certain conditions, such as the lack of heavy rains post-fire and the fire's geography, greatly limited its potential impact on the fishery. If the fire had burned in critical areas, such as the Killey and Funny

Figure 4.3.

Swan Lake Fire Burn Severity Map



River watersheds—which are key Chinook spawning areas—the fire would have raised much more concern, as interviewees described.

4.2.2 Resource unit impacts (interaction 5).

Fire has had little *direct* effect on fish. It is the post fire flooding and impacts to the resource system that affect fish most. Because the Kenai did not experience either of these, there was little concern that the Swan Lake Fire affected the salmon, steelhead, and in-river fish in the Kenai. Because of the way the fire unfolded, most interviewees quickly moved past this question onto the next area of impact: resource users.

4.2.3 Resource user impacts (interactions 6 and 7).

Despite the Swan Lake Fire's minimal impact to the resource system and resource units, the fire did have an impact on the resource users—primarily sport and personal use fishers. The fire did this by reducing access—through river and road closures—and deterring resource users from visiting the area because of fire danger and smoke. One interviewee explained this by saying, "On the anthropogenic end, there was a lot of stoppage of traffic and lack of access issues that were impeding people from coming down." The fire only burned near the river and Cooper Landing for a short period of time, so the reduction in visitation was roughly two to three weeks. However, given the short season of operation, many respondents in the service industry were financially affected by the fire because of the closures and uncertainty it brought. Interviewees working far down-river from the fire in Soldotna, AK, were still affected by it because Sterling Highway was periodically closed which cut off access from Anchorage, AK.

Communities closest to the fire—like Cooper Landing—were much more impacted, as one interviewee described: “businesses that had very timing specific incomes, like those in Cooper Landing, they felt it a lot more.” The level of concern reached the point where evacuations were being discussed for some communities along the Kenai. There was also an air quality advisory instated for the southcentral Alaska region because of the fire. Between closures, smoke, potential evacuations, and general fear and anxiety, fewer people traveled to the Kenai Peninsula, which resulted in a period of reduced visitation and lost revenue.

Interviewees working in the service sector—mainly outfitters and guides—described losses in revenue over this time. The older establishments said they were able to weather the effects of the fire because they were more financially secure and had good, long-standing relationships with their clients. Therefore, they could reschedule trips or offer refunds. Newer businesses expressed much more anxiety about the impacts the fire had on their business.

Looking at the fishery more broadly, we asked one interviewee to see if the fire had any effect on overall sportfishing effort. Explaining the results of this enquiry, the interviewee said,

> We actually had, in most cases, better than average effort and harvest. Now that corresponds with abundance; 2019 was a very good Sockeye year, so we did have a lot of effort and a lot of success. Looking through our general effort trends, there was not a significant drop-off. On the whole, the fire had little effect.

This interviewee mentions but understates the significance of the 2019 Sockeye return which likely offset the lull in visitation that occurred during the fire. For comparison, between 2017 and 2021, the early run of Sockeye on the Russian River ranged between 27,103 to 46,976 fish. However, in 2019, early run escapement was 125,942. As more fish return, and escapement goals are projected to be met, the Alaska Department of Fish and Game increases the number of fish people can harvest—i.e., increasing the bag limit. One interviewee described how angling does not follow a normal economic demand-supply model—it is the opposite. As supply increases, demand also increases. They went on to say,

> When you increase the bag limit from 6 to 9 or 12, people come from the woodwork—they're borrowing gear from their neighbors, you see people who have never fished before, but the opportunity is there, and it feeds on itself that way. The more fish we have, the more engagement we have, the more license sales were going to have, and the better data we are going to have to produce years like that.

This interviewee also draws a very important connection between fish abundance, angler engagement, and the funding to research, monitor, and manage the fishery. Because much of the Alaska Department of Fish and Game's funding comes from license sales, more angler engagement produces more funding. When runs are poor or anglers cannot access the resource, anglers are less engaged, which negatively affects funding for important management operations; and large salmon runs with good access produce more funding. Therefore, impacts to the resource system, resource units, and access to either, reduces the governance system's ability to manage.

The largest impacts to the Kenai fishery were to the resource users—particularly those in the service industry closest to the fire. However, this short decline in visitation was offset by large Sockeye run, which attracted many people to the region after the closures were lifted and the fire risk subsided. Even though total sportfishing harvest and effort was high in 2019, people in the service industry still described losses in revenue because they are constrained by the timing of the season. For example, if a guide loses two weeks of work during the season, they cannot make it up later because the season is over. Interviewees reflected on the uncertainty the fire created, and the reductions in income that came with it. All being said, the effects of the fire could have been much worse if the fire burned closer to, or through, the communities along the Kenai. As far as potential impacts fire can have on a fishery, resource users are the most vulnerable because they are subject to reductions in resource unit abundance, declines to access and visitation, and infrastructure damage.

4.2.4 Governance system's response to fire.

Our discussions with managers revolved around: 1) how managers are thinking about fire and the management of the fishery; and 2) how managers are thinking about the future of fire in a rapidly changing environment.

Historically, the fire interval on the Kenai Peninsula has ranged between 400- to 600-years (Berg and Anderson, 2006). Therefore, fire has only played a small role in the region, and some managers expressed that it was not at the forefront of their minds when conditions are "normal." Normal conditions on the peninsula are not conducive to fire, therefore fire is not an immediate concern most of the time. When conditions are good, managers are focused on putting out proverbial fires—dealing with the most pressing issues as they arise. However, if trends continue, this could change. One manager expressed how they prioritize threats by saying,

> If we had this conversation last year when it was hot and dry, I may have had a different answer. But with this year, and what I would call a more normal summer with our cloud cover and precipitation, fire is not a concern of mine. I am more concerned about the larger environmental drought situation, because it does have impacts on what we do as far as [fish] population health, and that in turn will change what we do with the user

> groups. It's always the first step. We are looking at the biological health and the sustainability of our resources, and then we adjust the anthropogenic affects to cope with those changes.

The Kenai fishery, with its large and complex resource system and diverse set of resource users, has a host of issues which can affect resource unit productivity. With the current management capacity, and the many issues managers are trying to address, unpredictable events loom, but do not take priority when more salient issues are present. One interviewee described the role of adaptive management in how they address unpredictable events by saying,

> When you were talking about environmental issues such as floods, fires, droughts, and the various things we cannot control, our management program is very adaptable and we are able to deal with these things as they come up so they're not as big of an issue. Adaptive management is very nice.

Given the unique role of each manager, they all expressed different views and concerns about fire. The quotes above express how these managers are thinking about fire as a 'we will cross that bridge when we get there' kind of issue. However, others described in detail how a rapidly changing population and environment are making the issues surrounding fire more pressing and complex. For example, one interviewee expressed how there is not a consistent baseline because the peninsula is currently a "rapidly transforming environment both in terms of how many people are here—moving here and recreating here—and in terms of environmental conditions." This interviewee describes how the anthropogenic and environmental conditions are making fire management more difficult. As more people move to, and recreate on, the landscape, it increases the potential for human-caused fires. In addition, more people on the landscape increase the urgency and complexity of firefighting efforts to provide safety and reduce property damage.

A rapidly changing environment was creating the most difficult conditions for managers to address—both now and in the future. The environmental changes they described included increased frequency of lightning. One interviewee said, “the Swan Lake Fire was one of seven or eight fires that started in a lightning bust that wouldn't have even happened 25 years ago on the Kenai Peninsula because we very rarely saw lightning, but now we're seeing more and more of it.”

In addition to the increased frequency of this historically rare fire starter, interviewees also described how the fire itself defied many expectations with regards to its behavior.

> Swan Lake Fire [burned] under extreme environmental conditions, which got more extreme as the fire season wore on. [We had expected] traditional cooler and damper weather to occur, [but it didn’t]. The whole thing was just a completely different situation.

Another aspect that defied expectations was how the Swan Lake Fire burned through areas that traditionally would have acted as natural barriers. One interviewee explains,

> The reality was that even with everything we had to throw at it, we were unsuccessful in keeping it where we originally wanted to keep it, so we kept having to fall back. Even if we had firefighters to throw out to the northern flank and the eastern flank going up into the mountains, the assumption was that fire does not burn up there. It's going to be a natural barrier and we are not going to put firefighters in danger. [Now we have] the realization that fire can burn in places under certain conditions that we haven't seen before.

To describe how extreme the conditions were, one interviewee said, “maybe the fire behavior models could have been better, but again, we are plugging in numbers that have never been plugged in before. The drought indices have hit levels that haven’t been measured before." Another interviewee said, "A lot of folks didn't realize what we saw during the Swan Lake Fire was even possible here in southcentral Alaska."

As fire frequency and intensity increases in an area that historically has not experienced these conditions, one interviewee said, "We're in the Anthropocene; we're in an era where we don't know what natural means anymore because entire ecological systems are being affected everywhere." These conversations about the changing environment were to preface the point some managers were making—that in a rapidly changing environment, all assumptions about the ecological outcomes of fire are in question. For example, the assumption that fire is good for the landscape, or how fire interacts with a fishery, may not hold true in our new reality. To this point, one interviewee said,

> It's not as simple anymore. [We used to say that we] like fire because it produces early seral habitat that benefits moose and other species… In a period of rapid environmental transformation, all of our assumptions about whether fire is good or bad, and where and when, may need to be revisited.

Another manager also described how his assumptions about fire are changing, by saying,

> We largely view fire as being positive on the landscape as long as it's away from communities and other locations. Most of the time we have a positive benefit associated with that. With the changing climate, we have more fire in more intense fire on the landscape; that may not be beneficial. We may start seeing issues that affect our salmon runs and start throwing things out of balance.

At this point, it is unclear how future fire scenarios will affect the fishery. It is a possibility that it may, overall, have little effect on the Kenai's productivity. However, given what we have found with the Swan Lake Fire, we can assume that increased fire will continue to affect resource users in various ways. As the Kenai, and salmon fisheries in general, experience rapid environmental change, we need to ask what, if anything, can be done to buffer them from the compounding social and ecological pressures placed on them. As one manager expressed above, the first thing they do is assess the “biological health and the sustainability of our resources” and then “adjust the anthropogenic affects to cope with those changes.” If environmental change and increased fire affect the “biological health and sustainability” of the Kenai, how are the “anthropogenic effects” going to be altered? If there is a decrease in salmon productivity, changes will need to be made that may have profound effects on the resource users, which we have already identified as the most vulnerable to fire events. Below we use our social-ecological systems model to outline a literature review of how fire can impact a fishery. From this review, we identify potential circumstances that may result in long-term negative effects.

4.3 Model guided literature review of fire impacts

One challenging aspect of outlining the impacts from fire to a fishery is that fire is a naturally occurring disturbance which has diverse and complex outcomes (Bisson et al., 2003; Moody et al., 2013; Brogan et al., 2019). For example, the outcomes of a fire are all related to the fire’s timing, location, extent, and severity in addition to the composition and structure of the burned ecosystem (Dahm et al., 2015; Greswell, 1999). In general, fire impacts a watershed by reducing canopy and ground cover, decreasing soil infiltration rates, and decreasing surface roughness (Benavides-Solorio and MacDonald, 2001; Benavides-Solorio and MacDonald, 2005; Ebel et al., 2012). These changes in the watershed increase the rate of surface runoff and erosion (Onda et al., 2008; Benavides-Solorio and MacDonald, 2001). Therefore, when a recently burned watershed experiences an intense storm with heavy rainfall, there is a high likelihood there will be post-fire flooding and debris flows (Brogan et al., 2019). It is the post-fire events which have the greatest impact on streams and stream fishes (Burton, 2005, Gresswell, 1999; Rinne, 2004), not the fire itself.

The literature review that follows is guided by the social-ecological model presented in Figure 2. Two strategies were used to identify how fire affects components of this model. First, using the model as a guide, we asked interviewees to identify how the Swan Lake Fire affected specific components of the Kenai fishery—the results of that process are presented above. Second, we systematically searched the literature for ways fire can impact each component of the model (e.g., how fire affects spawning habitat). Once we identified if/how fire affects each component of the model, we synthesized the information by connection. The results of this process are below.

4.3.1 Fire → Passage (Interaction 1).

Anadromous fish migration and passage has been a concern for many decades. As the amount of human development has spread across landscapes it has created many obstacles to fish movement and migration. Obstructions such as dams, irrigation diversions, and culverts can create obstacles making fish passage extremely difficult or impossible. These obstacles have severed entire populations of fish from their historic ranges (National Research Council, 1996; Lichatowich, 2001), and research has shown that upstream movement of juvenile, not just adult, fish is important and happens far more frequently than previously thought (Kahler and Quinn 1998; Kahler et al. 2001). The primary concern regarding fish passage in the Kenai River Watershed is culverts.

However, there are many man-made and natural passage issues that can arise in the event of a post-fire flood.

Given a fire may increase the likelihood of an extreme flooding event (Borgan et al., 2019), functional culverts, or other structures, may become impassable during post-fire flooding. The combination of post-fire flooding and debris can scour, block, damage, and ultimately alter a structure to the point where fish passage becomes extremely difficult or impossible. Therefore, after a fire, an assessment of vulnerable culverts and other potential impediments to fish passage should be evaluated and monitored. If an obstacle becomes difficult or impossible for fish to traverse, it should be addressed immediately to avert any long-term impacts to the fish population(s).

4.3.2 Fire → Spawning Habitat (Interaction 2).

Most fire events, which have a mild to low burn severity, have little to no impact on stream spawning habitat (Burton, 2005). Even though most fires will have little to no lasting negative impacts, with increasing frequency and severity it is important to understand how a fire event can affect spawning habitat, and the subsequent consequences.

High-severity fires occurring in the headwaters of a watershed greatly increase the likelihood of large geomorphological changes (Borgan et al., 2019). These changes are driven by potentially catastrophic flooding which scours the channel, sometimes removing gravel down to bedrock (Propst and Stefferud 1997; Roghair et al. 2002). Post-fire flooding, scouring, and the importation of fine sediments can cause large or total reduction in stream fishes (Rinne, 2004; Gresswell, 1999; Burton, 2005). Even when a particular stream is highly impacted by post-fire flooding, the spawning habitat usually improves after the system has had a chance to recover, which can take anywhere from three to ten years (Burton, 2005; Reeves et al., 1995; Sedell et al., 1990, Benda and Dunne, 1997, May and Gresswell, 2004). Consequently, the impacts to spawning habitat, are most often classified as short-term impacts.

There is, however, the possibility of long-term impacts. For example, different species, and even different stocks may have unique and different preferred spawning habitats. Burger and others (1985) found specific populations of Chinook salmon (*Oncorhynchus tshawytscha*) in the Kenai River utilized different spawning habitats at different times. Interviewees described their concerns of a fire occurring in the headwaters of the Funny and Killey Rivers, because they support early-run Chinook. There is evidence to suggest diverse and interconnected watersheds give fish the ability to choose alternative habitats in the face of a disturbance event, which protects the population against the loss of one habitat (e.g., a spawning area) (Burton, 2005). One example is when steelhead (*Oncorhynchus mykiss*) sought out alternative spawning habitats after their natural habitats were altered by the volcanic eruption of Mount Saint Helens (Leider, 1989). The populations least vulnerable are those living in interconnected stream networks providing a variety of habitat alternatives.

The populations most vulnerable to long-term impacts are isolated, lack quality habitat alternatives, and are low in numbers (Burton, 2005). Even without a disturbance, isolated populations of stream fishes are at a much greater risk of extirpation (Morita and Yamamoto, 2002). Given this, isolated populations, especially those in low numbers, are extremely vulnerable because nearby populations cannot repopulate them. In addition, if a population is already threatened, and post-fire flooding and debris flows impact the current population and impact the spawning habitat for multiple cycles, then that population loses recruits and becomes more threatened or extirpated. Ultimately, high intensity fires will have the greatest long-term impacts on fish populations that are isolated, do not have alternative habitats, or are already low in numbers. If this is the case, then mitigation strategies should be considered to reduce impacts.

4.3.3 Fire → Rearing Habitat (Interaction 3).

Rearing habitat is also incredibly important for producing fish. Juvenile fish occupy a diverse set of habitats as they move through their life cycles. These habitats function to protect and feed young fish, and with anadromous fish, these habitats get them to the point where they can migrate to the ocean.

Fire can affect rearing fish and habitat in multiple ways. First, extreme post-fire flooding events and debris flows are capable of extirpating fish from a stream (Propst and Stefferud 1997, Roghair et al. 2002), which is a direct and immediate impact on rearing fish. Fire also removes riparian vegetation which can alter nutrient inputs and macroinvertebrate populations, disrupting food chains (Minshall, 2003). These changes, in addition to the possibility of the stream channel being scoured and incised to a degree that may make the stream unsuitable, can affect juvenile fishes for years (Minshall, 2003; Burton, 2005).

Most fires result in insignificant impacts to fisheries. The effects of most small-scale fires to rearing habitat can largely be classified as short-term impacts because most streams usually transition back to something resembling their prior state within one to ten years after a burn, even in the case of a catastrophic post-fire flood (Minshall, 2003; Burton, 2005; Reeves et al. 1995; Sedell et al. 1990, Benda and Dunne 1997, May and Gresswell 2004). The impacts to rearing habitat are most concerning with vulnerable and/or isolated populations. After a catastrophic event, reaches are generally repopulated by unaffected areas or refugia (Burton, 2005). The Kenai River is such a large, complex system, there are potentially many ways for a particular stock to be repopulated. However, populations already facing sustainability challenges—such as Chinook—may warrant special considerations after a fire event.

4.3.4 Fire → Water Quality (Interaction 4).

Fire alters soil and vegetation characteristics, which affects nutrient transport and water quality (Gresswell, 1999). One effect is increased stream temperature, which is a result of reduced canopy and riparian cover, exposing streams to more direct sunlight (Ice et al., 2004; Burton, 2005). Temperature increases have a wide range of possible outcomes. For example, if a species is living in an environment at the lower end of their temperature threshold, an increase in water temperature can increase the productivity for that species potentially resulting in stronger age classes (Donald and Alger, 1986). However, when temperature increases exceed a species threshold there will likely be a decrease in that species' productivity (Jones et al., 2020). In some observations (e.g., Burton, 2005), increases in stream temperature resulted in no statistically significant difference in fish populations between burned and unburned watersheds. There have, however, been recorded incidents of drastic spikes in stream temperature with associated fish mortality (Brown and Krygier, 1970; Amaranthis et al., 1989). It is important to note that stream temperatures have been increasing across western North America (Al-Chokhachy et al., 2017; Isaak et al., 2012; Leppi et al., 2012; Rood et al., 2005; Stewart et al., 2004, 2005), which mostly are driven by higher air temperatures (Issak et al., 2012). The combination of lower than average flows and warmer than average temperatures can result in large and impactful fish kills (Lamborn and Smith, 2019). As this warming trend continues and more cold-water habitats reach their upper threshold, the threat of fire-related warming could be a more impactful phenomenon than it has been in the past.

Fire can also increase nutrient inputs into water, which can have a wide range of effects. One extreme example is postfire flooding and debris flows, which can heavily alter stream characteristics and potentially extirpate a fish population (Rinne, 2004). Large pulses of sediment resulted in fish mortality up to two years after the 1988 Yellowstone fire (Bozek and Young, 1994). Most fires, however, fall in the low- to mild-severity, and can increase the productivity of a system leading to increased recruitment and growth rates of fishes (Kelly et al., 2006). With >100 years of fire suppression, large quantities of nutrients have built up that are released via smoke, ash, and water transport, which enrich nearby water bodies with phosphorus and nitrogen and increase the risk of eutrophication (Spencer et al., 2003). In addition, fires increase the concentration of mercury in fishes, which can cause health concerns for people who consume them (Kelly et al., 2006). There have also been cases where fires may be linked to increase in metals, like copper (Ignatavièius et al., 2010), which are very toxic to salmon species, especially Coho (Baldwin et al., 2009).

There has also been a debate over whether certain chemicals used in fire retardant affect fish. The USDA Forest Service stopped using retardants with sodium ferrocyanide in 2007 because of the potential toxicity to aquatic organisms (USDA, 2007). The replacement chemical, PhosChek, was less toxic in laboratory experiments (Little and Calfee, 2003). Although somewhat controversial (NMFS, 2007), the Forest Service has concluded that PhosChek poses very little risk to aquatic organisms (Comas, 2007; USDA, 2007).

There are also other impacts, such as decreased dissolved O_2 and changes in pH (Dahm et al., 2015), but as with most of the interactions we identified, effects are short-term. As canopy and riparian cover return, soils stabilize, and nutrient inputs decrease, systems generally return to a pre-fire state.

4.3.5 Fire → Fish Populations (Interaction 5).

Fire and post-fire disturbances can drastically impact fish populations (Burton, 2005, Gresswell, 1999; Rinne, 2004). However, the outcomes of fire to a fish population are highly variable. In most cases, low- to mild-severity burns have very little impact on stream fishes. Even in the case of high-severity burns, fish populations tend to recover within a decade after the burn. For example, one year after a high-severity fire, Burton (2005) observed a complete removal of fish in affected streams. However, as the habitat recovered, redband trout (*Oncorhynchus mykiss gairdneri*) repopulated these streams. Burton (2005) concluded by saying, "…in the case of uncharacteristic wildfires, local extirpation of fishes is apparently short-term and patchy, recolonization is potentially rapid, and habitats disrupted immediately after the flood events are often rejuvenated within 5–10 years" (p. 144).

Streams experiencing large or total reductions in fish populations rely on re-population from downstream or unaffected habitats (Burton, 2005; Rieman et al., 1997). There are factors, such as isolation, that increase the likelihood of fire having large and possibly long-term impacts (Burton, 2005; Morita and Yamamoto, 2002; Propst et al., 1992). For example, Morita and Yamamoto (2002) found white-spotted charr (*Salvelinus leucomaenis*) occupied all of the undammed streams they sampled, and were absent in 33% of dammed streams. They also found that as the isolation period increased and habitat size decreased, there was a higher likelihood of extirpation. Just from isolation alone, they forecasted extirpation of an additional 34% of the remaining populations in the next 50 years if migration barriers were not altered or removed. Fire can expedite this process, and some research has documented populations of brook and rainbow trout that never recovered after a fire, which is likely attributed to their isolation (Rinne, 2004). In addition to isolation, Dunham and colleagues (2003) hypothesized that decreased habitat size, habitat degradation, and a high level of habitat specificity all contributed to a population's vulnerability to fire and post-fire disturbance. Even when there are no impediments on re-population, research suggests salmonids tend to be the slowest to recover after a post-fire disturbance, with a range of ~30 days to six years (Detenbeck et al., 1992). In summary, low to mild severity burns will have little to no impact on fish. High severity burns and subsequent post-fire disturbances can have a dramatic effect on fish populations, but most will recover within a decade. Isolation, habitat degradation, and a high level of habitat specificity can all contribute to long-term impacts to fish populations after a disturbance.

4.3.6 Fire → Resource Users (Interactions 6 and 7) and the Governance System.

In our literature review, we were able to find many peer-reviewed papers exploring the effects of fire on the resource system, and to a lesser extent, resource units. However, we were unable to find any literature on how fire affects resource users and the governance system. Therefore, the interview data we present here, to our knowledge, is the only information on this topic in the peer-reviewed literature.

4.4 Demonstration of the Model's Utility

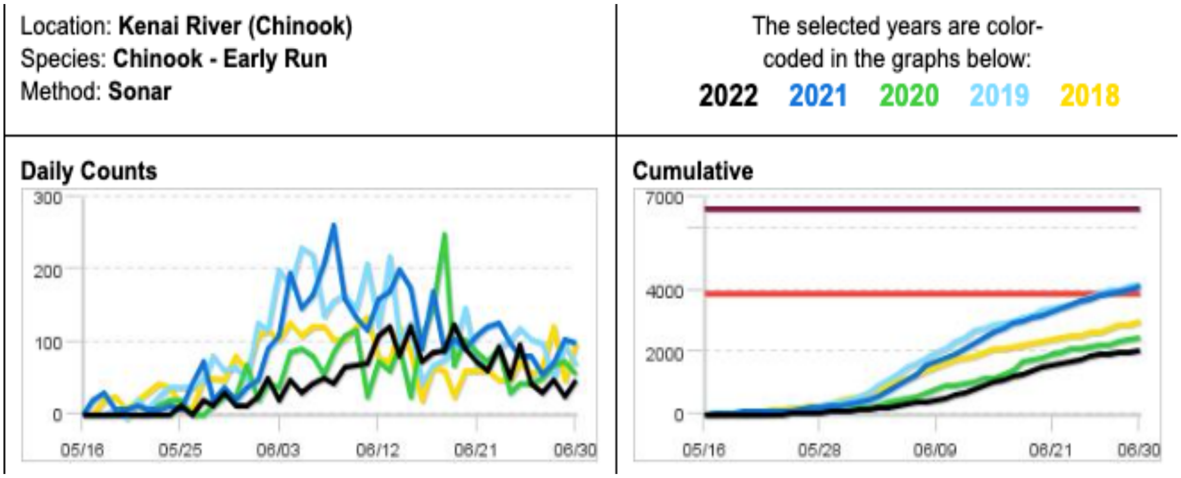
Throughout the results, we identify areas where potential short- and long-term impacts may occur. Here, we summarize those impacts and demonstrate how they could play out in the Kenai fishery. We use early-run Chinook salmon as an example because they are the most likely to be critically affected by fire, and in turn, affect the overall fishery.

In recent years, Chinook have exhibited an alarming downward trend, regularly missing their minimum escapement goal of 3,900 fish (Figure 4). To help meet minimum escapement, heavy restrictions are placed on resource users to allow for Chinook passage.

These restrictions come with heavy costs. Specifically, restrictions placed on resource users impact their ability to access and profit from the fishery and its other bountiful species (e.g., sockeye). Given their low abundance, and the broader effects they impose on the fishery, Chinook are the most critical issue on the Kenai. Therefore, the

Figure 4.4.

Early-Run Chinook Escapement



threats fire pose to early-run Chinook can have large social and biological impacts. We outline the process below.

4.4.1 Fire's impacts on the resource system and resource units.

The processes in which fire and post-fire flooding can impact a resource system, which then affects resource units, is clearly identified in the literature. As discussed above, many of these impacts are short-term and fisheries become as, or even more, productive three to ten years post fire (Burton, 2005; Reeves et al., 1995; Sedell et al., 1990, Benda and Dunne, 1997, May and Gresswell, 2004). However, in certain cases, fish populations can be quite vulnerable to long-term impacts. Specifically, the most vulnerable populations are isolated, lack quality habitat alternatives, and are low in numbers (Burton, 2005; Dunham et al., 2003; Morita and Yamamoto, 2002). We illustrate these three points within the context of our example.

First, early-run Chinook are genetically isolated. They spawn in a particular place at a particular time, and they are genotypically and phenotypically different than other

Kenai Chinook. Second, early-run Chinook have specific habitat requirements, spawning in the Killey and Funny River tributaries (Burger et al., 1985). There is evidence that anadromous fish will seek out alternative habitat in the case of a large disturbance (Leider, 1989), but it is unclear if early-run Chinook will exhibit this same behavior. If they did, it may result in genetic mixing with other populations which poses the potential of losing this unique population. And third, early-run chinook are low in numbers, as we have discussed above.

If a high-intensity fire occurred in the headwaters of the Killey or Funny rivers, there is a high probability that Chinook abundance would suffer. At the very least, any further declines in early-run Chinook abundance, even if they are temporary, will greatly impact the broader social-ecological dynamics of the fishery. The worst-case scenario would be that given their current vulnerabilities, early-run Chinook may be subject to long-term declines that may threaten the population's sustainability.

4.4.2 Resource users.

Regardless of whether fire creates short- or long-term impacts to early-run Chinook abundance, the fishery is currently being utilized to a point where any reductions would create great hardships for the resource users who are already suffering the effects of low Chinook abundance. Any further restrictions could likely push additional commercial and sport fishers out of business, and increase tensions among resource users, and between resource users and the governance system.

4.4.3 Governance system.

The governance system is the mediator of the Kenai fishery. It oversees the resource system, resource units, and resource users. There is already great tension among resource users, and between resource users and the governance system. Interviewees expressed how the public blamed the governance system for not putting out the Swan Lake Fire sooner and allowing it to get as big as it did. In turn, the governance system was caught off guard by the extreme environmental conditions that defied expectations and assumptions. If a fire did affect the fishery by reducing abundance, which led to further restrictions, the tension between resource users and the governance system could be exacerbated. In addition, long standing conflicts between resource users could also become worse.

Ultimately a fire that resulted in short-term impacts to early-run Chinook abundance has the potential to set off a chain of negative interactions that will play out most intensely among resource users and the governance system (Figure 5). This puts the governance system in a difficult place because they are trying to understand how to manage fire in a rapidly changing environment that has the very real potential to create sustainability issues for resource units and resource users. Therefore, fire has great potential to exacerbate existing challenges already faced by the governance system.

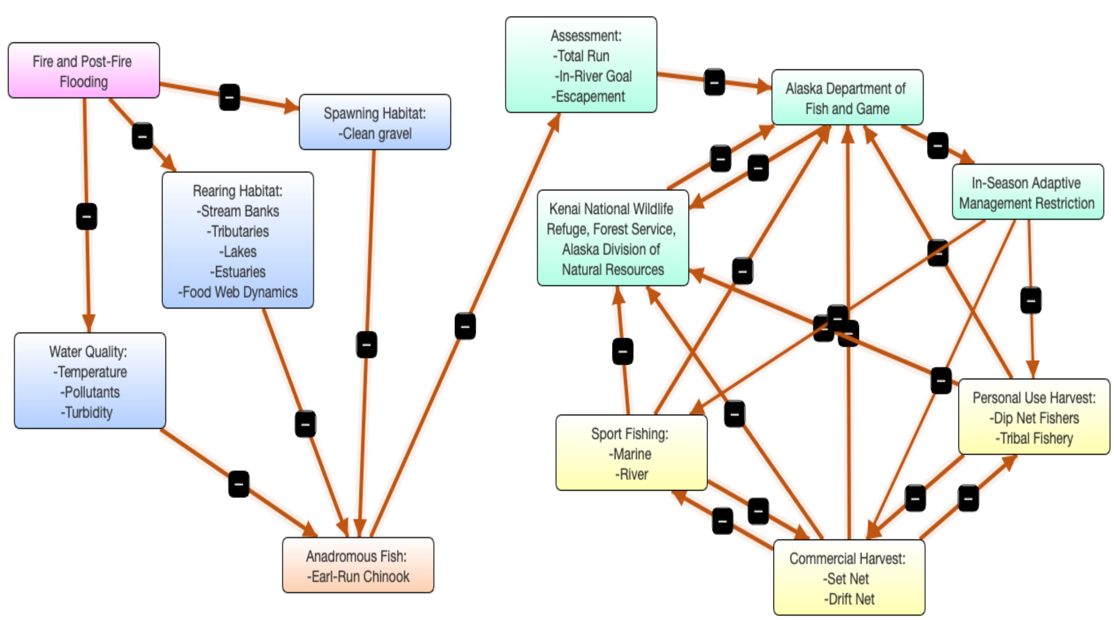
What can the governance system do to prevent this chain of negative interactions? Currently, the governance system is faced with environmental forces that are beyond its control, such as increased lightning frequency, prolonged drought, and warmer temperatures. These factors are increasing the frequency and severity of fire in a system with a historically low fire frequency. In a remote watershed that is not heavily fished, these rapid environmental shifts may, or may not be concerning. Throughout time, salmon have proven to be resilient in the face of environmental change and disturbance. Although, there is evidence that climate driven changes in freshwater systems are causing issues (Jones at al., 2020). The reason why fire poses such a great threat to the Kenai is because it is being utilized so heavily and low chinook abundance is already causing these issues to play out. Any further reduction in chinook abundance will make the situation worse.

5. Discussion

As demand for food and experiences grow, fisheries around the world are being utilized to, or over their capacity (Pauly and Zeller, 2017). In addition to the varied social demands on fisheries, compounding environmental pressures are also pushing fisheries to a breaking point. With these many pressures, disturbance events, such as large, highly intense wildfires can alter the productivity of a fishery and the stability of the broader

Figure 4.5.

Potential Chain of Negative Ecological and Social Interactions Initiated by a Fire



social and ecological systems in which they are embedded. To shed light on these issues, we utilized a mixed methods approach to develop a generalizable model and used it to explore the impacts of wildfire on the social and ecological components of the Kenai fishery.

This framework was developed using a novel method that involved collaboratively building models with diverse stakeholders. We used fuzzy cognitive mapping (Kosko,1986; Ozesmi and Ozesmi, 2004) with the software Mental Modeler (Gray et al, 2013) to develop social-ecological models grounded in Ostrom's (2007; 2009) social-ecological framework. Once the foundational social-ecological model was complete, we then identified how fire affects each component of the model through stakeholder interviews and literature review, identifying specific circumstances where fire can lead to long-term impacts. Lastly, we used this information to detail of how fire in the headwaters of the Killey and Funny rivers could have cascading negative interactions throughout the fishery.

One of the unique findings of this work is that resource users are, in various ways, the most vulnerable to fire and its impacts. Even though the Swan Lake Fire had little impact on the resource system and resource units, it did have an impact on resource users—specifically the sport and personal use fishers. The sector of the sportfishing community that was hit the hardest were those closest to the fire in Cooper Landing, AK. One interviewee explained that under Magnuson-Stevens Fishery Conservation and Management Act of 1976, the sport fishery can only access "disaster relief [funds if the] commercial fishery also experiences a disaster, which is a 35% economic loss against the five-year average." This interviewee went on to say, "those folks in Cooper landing definitely had a greater than 35% loss but had no access to federal disaster relief funds." We were unable to confirm the specific amount of economic loss accrued by the sport fishery. Regardless, the main takeaway is that unlike the commercial fishing industry, the sport fishing industry—which is a large sector of the region's economy— has, under the current law, no access to disaster relief even though it is the most vulnerable to fire.

This research, more broadly, details a way in which complex social-ecological systems can be broken down into a set of variables and interactions, which in turn can be used to address complex questions. The social-ecological model we developed is specific to the Kenai fishery. However, with small adaptations, it can be altered to represent a wide range of fisheries throughout the world. We have shown how this model can be used to: 1) guide discussions with stakeholders; 2) organize information; and 3) assess vulnerabilities and possible outcomes. Beyond fire, this model can be used to assess a wide range of exogenous and endogenous forces being placed on fisheries, and in turn, potential outcomes, vulnerabilities, and opportunities.

Taking a social-ecological approach at this scale requires a broad lens. Although this method allows us to map complex systems, the outcomes are rough representations. One positive of this method is that it allows us to map many interactions where no data exists, where the connections are 'fuzzy.' The components of the system are well accounted for; however, the interactions are broad representations. As one interviewee said, "I could make an argument for there to be a connection between every variable in this model." Therefore, this general representation of interactions should be assessed with caution and should likely be altered depending on the research question being addressed. Lastly, we are attempting to depict a very complex and dynamic system that is constantly changing. The outcome of our work is not intended to be a model that can used to compute outputs given a specific set of inputs. Just trying to model how the resource system affects resource units in a fishery often results in mathematical chaos. Trying to also incorporate the resource users and governance system is simply out of the realm of possibilities. Therefore, it is best to use this and similar models as broad representations that can be used as a tool for exploring ideas, organizing information, and leading conversations.

Overall, we hope this work provides a roadmap for others who are interested in exploring complex social-ecological systems. Fisheries are extremely difficult resource systems to manage sustainably. Although fire is just one of many stressors, we hope this work can help those thinking about and addressing the many endogenous and exogenous stressors that may affect the sustainability of social-ecological systems.

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CHAPTER V

CONCLUSION

1. Summary of findings

The three studies presented in this dissertation expand our understanding of how social and ecological components of fisheries are affected by endogenous and exogenous pressures. The first study (Chapter II) expands our understanding of how shifting runoff cycles affect angling on the Yellowstone River (Montana, USA). The second study (Chapter III) utilizes an innovative method to develop a social-ecological model of the Kenai fishery (Alaska, USA). It then demonstrates how a social-ecological model can be used to identify factors promoting or impeding the fishery's sustainability. The third study (Chapter IV) demonstrates how a social-ecological model can be used—i.e., interview guide, structured literature review, scenario exploration—to explore how a disturbance event such as fire can affect a system and identify vulnerabilities for long-term impacts.

Study 1 (Chapter II). Runoff cycles are shifting throughout the western United States, with widespread and varied ecological and social effects. The purpose of this study was to document if people perceived changes in runoff, if/how changing runoff has affected the social and ecological components of the Yellowstone River, and if/how people are adapting to the challenges associated with drought conditions and changes in runoff. We were able to identify that: 1) people are perceiving the recent shifts in hydrology (i.e., earlier runoff, shorter and more intense runoff, increased annual variability, and warmer water temperatures); 2) there are social and ecological impacts from these shifts; and 3) people are employing strategies to help them cope with these changes. Some of what interviewees described has been documented in peer-reviewed scientific literature, and that information was corroborated where possible. However, this research expanded the discussion of shifting runoff to include a more comprehensive picture of what effects shifting runoff is having. Ultimately, there is a shrinking resource with many increasing demands. Recreational use of the Yellowstone River has been increasing sharply over the last decade, and lower flows and higher temperatures are affecting the resource and, at times, the angling experience. Although these changes are gradual, they are occurring, and some faster than expected.

Study 2 (Chapter III). This study utilized Fuzzy Cognitive Mapping (Kosko, 1986) and Ostrom's (2009) social-ecological framework to collaboratively develop a social-ecological model of the Kenai fishery in Alaska. By using Ostrom's framework as the foundation for the model-building process, this innovative method improves the development of social-ecological models and increases the comparability of models across different social-ecological systems. In addition, the models developed using this method can: 1) illustrate the breadth and interconnectedness of a social-ecological system; 2) be used to facilitate discussions around management; and 3) be used to explore the components and interactions moving a system toward or away from sustainability. Using the model of the Kenai fishery, I identify how the nature of salmon (migratory) and their habitat (large and unpredictable) leads to uncertainty about effective management strategies. This uncertainty, in addition to a large and diverse set of resource users, creates conflicting management visions which ultimately paralyze a governance system operating under collective-choice rule.

Study 3 (Chapter IV). As fires become more frequent and severe, we need information and tools that can help us understand the broad scope of impacts fire can have. In this chapter, I identify the scope of impacts fire can have, and provide a model to organize information and think through scenarios. In addition, I also show how the model can be a useful tool to guide discussions with stakeholders and assess vulnerabilities and possible outcomes. With this information, I identified that fish populations which are isolated, lack quality habitat alternatives, and have low abundance are the most vulnerable to long-term fire-related impacts. Applying this to the Kenai, I conclude early-run Chinook salmon are the most vulnerable to fire, and if impacted, early-run Chinook have the greatest potential to severely impact the fishery more broadly through a chain of negative interactions. Beyond fire, this model can be used to assess a wide range of exogenous and endogenous forces being placed on fisheries, and in turn, potential outcomes, vulnerabilities, and opportunities.

2. Research Contributions

The research presented in this dissertation contributes in two ways. First, it expands our understanding about how fisheries can be impacted by endogenous and exogenous social and ecological pressures. Second, it builds upon previous methods to develop social-ecological models that can be used to organize our understanding of complex systems and the problems they face. Specifically, this research provides insights into how shifting runoff and fire affect fisheries. In addition, this research uses an innovative method to model the Kenai fishery that improves the breadth and comparability of future social-ecological models.

3. Limitations

Every research method has shortcomings. The research in this dissertation heavily utilized qualitative data collection and analysis methods. These methods are good for gaining depth and context, but they heavily rely on the perspectives of a select few people. I worked to ensure that the perspectives gained through this research were from reputable sources from diverse backgrounds to minimize biases. I also used peer-reviewed literature to support areas of this research where possible. Below, I describe the advantages qualitative methods provided in each study and the limitations of the research.

In Chapter II, I wanted to expand the discussion of shifting runoff cycles beyond the phenomenon itself to include the broader social and ecological implications. This was a new area of research where the implications were unknown. Therefore, qualitative methods provided the opportunity to explore this topic in a way that reduced my assumptions and biases. For example, if I developed a questionnaire that could be distributed to a representative sample, the questions would have been conceptualized by me using my own experience and the limited information related to the topic. This approach would have restricted the scope of work and would have not have provided a comprehensive account of what is occurring. One limitation of this work is that it presents the perspectives of a select few, albeit knowledgeable, individuals, and therefore is not representative of the broader angling community. However, now that this initial step has been taken, the information in Chapter II provides the conceptual foundation for subsequent efforts to take a quantitative approach to further explore the implications of shifting runoff. Additional quantitative efforts could help us better understand the frequency, extent, and severity of social and ecological impacts related to shifting runoff cycles.

In Chapter III, I wanted to take a step back from common social-ecological research focusing on the interactions of a small subset of variables. Instead, I wanted to create a model that comprehensively depicts the structure and function of a salmon fishery. This could not be done with traditional modeling approaches because salmon fisheries are complex, and many interactions lack data. With regards to complexity, efforts to model portions of a salmon fishery have been unsuccessful due to their chaotic nature (Acheson et al., 1998, Filipe et al., 2010). Therefore, I needed a method that could manage the complexity and identify the nature of relationships between variables without relying on quantitative data. Fuzzy cognitive mapping was developed by Kosko (1986) to do just that, and it has been used across a wide variety of fields to understand the structure and function of complex systems. In addition, I wanted to introduce additional structure to fuzzy cognitive mapping in the field of natural resource management. Therefore, I structured the development of fuzzy cognitive maps around Ostrom's (2007; 2009) social-ecological system framework. As a result, I was able to collaboratively develop a social-ecological model of the Kenai fishery. However, as with all modeling processes, the final model has limitations. Although it is likely the most comprehensive model of the Kenai fishery to date, it is not a perfect representation. It is a general model that shows the overall structure and function of the fishery, and as depicted, does not provide the specific detail needed to address many research questions. However, it is a useful representation that can act as a foundational starting point for future work. In Chapter IV, I illustrate how this model can be used as a guide to add structure to discussions and literature reviews. I also show how it can be used as a tool to explore scenarios and potential outcomes. Overall, there are two key takeaways from this work: 1) I provide a method for modeling the structure and function of complex natural resource systems; and 2) I provide a general model of the Kenai fishery that has a variety of uses, which I detail in Chapter IV.

In Chapter IV, I used a mixed methods approach to increase our understanding of the social and ecological impacts fire can have on a fishery. To do this, I used the model developed in Chapter III as an interview guide to explore how stakeholders were affected by a recent fire. In addition, I use the model to structure a literature review. Lastly, I used the model to explore fire scenarios that may result in long-term impacts. As an interview guide, the model proved to be a useful tool in identifying social and ecological impacts of fire. Given the nature of qualitative data collection this was a relatively small sample, which I tried to offset with peer-reviewed literature where possible. The peer-reviewed literature was helpful in identifying the impacts fire has on habitat and species, but it did not provide information about how the social components of a fishery are affected by fire. Therefore, qualitative methods proved to be useful in cataloging a more comprehensive list of impacts and the interactions of impacts within a fishery. However, given the complexity around fire impacts (e.g., timing, severity, location, etc.), this approach did not yield a predictive model. Instead, I was able to outline the extent of possible impacts and provide some general conclusions about what conditions and events may culminate in long-term impacts.

4. Future research direction

For the research presented in Chapter II, the next logical step would be to quantify the frequency, extent, and severity of social and ecological impacts related to shifting runoff cycles. This could be done by surveying the broader angling community. This approach would help us better understand who is being affected and where the effects are most pronounced. There is also the question of whether anglers are being displaced by these shifts in runoff. If they are, where are they going, and what should we expect from this increase in use during that specific time? In addition, there is the question of whether the general angling public is concerned about high water temperatures, the impacts to fish, and whether these anglers are altering their angling practices to reduce their impacts during stressful conditions (similar to outfitters and guides).

The method presented in Chapter III provides a way to model social-ecological systems using a common foundational structure. This was used to model the Kenai fishery. Future research can use the same approach to model other natural resource systems to address the issues they are experiencing. For example, this method could be used for mule deer (*Odocoileus hemionus*) in Utah (USA) to conch (*Aliger gigas*) in Quintana Roo (Mexico). Further work using this method will hopefully provide additional insights to improve the method and its ability to address complex problems.

Lastly, the model presented in Chapter III was used in Chapter IV to illustrate how fire affects a fishery. This was just one example of how this model can be used. The work presented in this dissertation is largely focused on ecological pressures (e.g., shifting runoff and fire) and the broader social and ecological impacts that result. However, this same approach can be used to explore a host of endogenous and exogenous pressures which can provide insights into many questions pertaining to sustainability. For example, there is more work that can be done to explore how social dynamics create incentives for, or instances of sustainability paradoxes (Singleton, 2000). Future research can use these models as roadmaps to explore the many pressures put on social-ecological systems and the outcomes that may result.

5. Concluding remarks

This dissertation contributes to our knowledge on how social-ecological systems are affected by endogenous and exogenous pressures. Using a variety of qualitative methods, I was able to catalog how two very different pressures (i.e., shifting runoff and fire) affect two different fisheries (Yellowstone River and the Kenai). In addition, I provide a method that can be used to model social-ecological systems to expand our understanding of how unique systems are structured and how they function. Collectively, these three studies improve our understanding of social-ecological systems and provide methods to continue this work in the future.

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APPENDIX A

SUPPLEMENTRAY MATERIALS

Introduction

The supplementary materials provide more information about the specific components within the final aggregated model of the Kenai fishery (Figure 6 in Chapter III). This section is organized by each second level variable in the resource system, resource units, and resource users. It provides a review of the peer-reviewed literature and government reports related to each specific topic.

1. Resource System

1.1 Passage

Passage refers to a fish's ability to move through their habitat unimpeded. It is critically important that both anadromous and resident fish have the freedom to move throughout their habitat to complete their life cycles, but to also find food and escape stressors and threats. Although there are natural barriers to passage, human created barriers have created the greatest challenges and impacts to fish populations throughout the world.

Like many rivers in Alaska, the Kenai River is not dammed and does not have any large water diversions. Therefore, the two main concerns mentioned by interviewees were culverts that impede passage and naturally occurring low flows. For fish to successfully navigate through culverts they must be able to enter, traverse the length, and exit the opposite side. In a review, Kahler and Quinn (1998) outlined the challenges to fish passage that culverts can impose. For example, when confronted with a culvert, the first obstacle fish encounter is entering the culvert. Here, they may be faced with an obstruction, excessive outlet velocity, or an impassible perch height (this is where the mouth of the culvert is above the streambed, creating a waterfall). If they can enter the culvert, they then must traverse the length of the barrel, where they may encounter excessive water velocity or inadequate water depth. Then to exit the barrel, fish are sometimes met by excessive velocity or obstructions, such as accumulated debris, which impedes travel. A lot of effort has gone into replacing old culverts with larger culverts that also accommodate the streambed and banks. The updated culverts allow the stream to pass through the culvert as if it were not there. Although many improvements have been made to improve fish passage, some outdated culverts still exist, which are, or may become, impediments to anadromous and resident fish migration.

In addition to culverts, interviewees also mentioned drought conditions that may render waterways impassible because of low water levels and/or warm water temperature. Low water levels are correlated with high water temperature. Therefore, drought conditions can create major impediments to salmon migration. Atlas et al. (2021) found water conditions can become so low and warm that adult sockeye will cease migration. Mortality of juvenile salmon also increases substantially during their out-migration when water conditions become low and warm (Marine and Cech, 2004; Singer et al., 2020). Climate change is likely to make these issues more frequent and severe.

When we take into consideration the full scope of salmon habitat, there are many more human-caused obstructions to fish passage than culverts alone. Human caused blockages to pacific salmon migration started to become a common occurrence in the mid 1800s (Lichatowich, 1999). As the amount of human development spread across the landscape, it created many obstacles to fish movement and migration. Obstructions such as dams, irrigation diversions, low water levels, as well as culverts create obstacles that make fish passage extremely difficult or impossible. Some of these obstacles have severed entire populations of fish from their historic ranges (National Research Council, 1996; Lichatowich, 2001), and research shows that upstream movement of juvenile, not just adult fish is important and happens far more frequently than previously thought (Kahler and Quinn 1998; Kahler et al. 2001). Just in the Columbia River Basin, dams alone have blocked approximately 55% of salmon's historic range (Service, 2011). In areas that are more developed, such as rivers in California, Oregon, and Washington, salmon face far more obstacles like low water levels, warm water temperatures, dams, and other obstructions that impede salmon in- and out-migration. As the climate warms, and drought becomes more frequent and severe, issues, conflicts, and disputes over water allocation and endangered species are likely to become more prevalent.

1.2 Spawning habitat

Interviewees described how important it is to have diverse, high-quality spawning habitat. Diversity is important because each salmon species, and even populations within a species, have specific requirements for spawning. For example, water temperature, depth, speed, and chemistry are all important (Lisi et al., 2013), so too is the size and location of substrate. Utilizing unique combinations of these conditions, distinct populations of sockeye in the Kenai River spawn in different areas, including the main stem, tributaries, and lakes (Seeb et al., 2000). These genetically distinct populations home with incredible accuracy to their natal stream and lakes, helping keep them genetically distinct (Seeb et al., 2000). In addition, Burger and others (1985) described the spawning characteristics between two populations of chinook salmon (*Oncorhynchus tshawytscha*) in the Kenai River, identifying how both populations utilized different spawning habitats and spawn at different times. Early-run kings, which are larger on average, spawn in large tributaries like the Funny and Killey Rivers. Late-run kings, which is the larger run but smaller fish, spawn in the mainstem of the Kenai River (ADF&Ga, N.D.). These two examples show how individual species, and populations within species, seek out and require specific spawning habitats.

The other important part of this equation is high-quality habitat. Changes in the many specific criteria required by salmon can directly affect the quality and amount of available habitat. One additional component that came up repeatedly in interviews was the importance of clean gravel (i.e., gravel clear of fine sediments that allows for interstitial flow that oxygenates eggs). Fine sediments are introduced into streams and rivers via surface runoff, and more fine sediments are introduced when there are natural or human-caused disturbances to ground stabilizing vegetation. When fine sediments settle over fertilized eggs, the eggs can suffocate and die. A meta-analysis of available data reported that salmon egg survival dropped rapidly when fine sediment less than 0.85mm reached 10% of the substrate (Jensen et al., 2009). This study also found that Coho (O. kisutch) were the most sensitive to fine sediments and chum (O. keta) were the least sensitive.

In the Kenai, as many areas of Alaska, human introduced fine sediments are a relatively low concern given the amount of high quality, relatively untouched habitat. However, there are some natural disturbances such as flooding and fire events that can introduce fine sediments, but the impacts of these are highly varied. Other salmon populations face many more fine sediment inputs, although much work has gone into reducing these inputs from activities such as construction, grazing, logging, mining, etc. The impacts from these activities were most prevalent in the 1800s and early 1900s (Lichatowich, 1999). There are many regulations and precautions to reduce the effects of fine sediments in many waterways today.

1.3 Rearing habitat

Given their migratory nature, salmon utilize a wide range of habitats as they grow to prepare to enter the ocean. The components of rearing habitat that were mentioned by interviewees were estuaries, lakes, stream banks, tributaries, as well intact and functioning food webs. Recreational use and human development have a lot of potential to heavily degrade salmon rearing habitat. Although many of the upper reaches of the Kenai River offer high-quality habitat, the lower river—and other specific areas where use congregates (e.g., Russian River)—have endured severe habitat degradation. Waterfront development, boat use, and recreational foot access are all contributors to degrading the quality of rearing habitat. Realizing the issue, a comprehensive and well-funded effort was initiated in the mid-1990s to protect and restore salmon habitat in the Kenai River watershed. Specifically, this effort was focused on restoring riparian habitat, purchasing land that contained critical habitats, providing low-impact river access to anglers, and creating a development plan to protect the watershed’s function and integrity (Weiner, 1998).

1.3.1 Stream banks

A lot of effort has been invested in restoring the banks of the Kenai River. Stream banks that offer complex cover such as rootwads, debris jams, and overhangs are incredibly important for juvenile salmon, and these areas are often where the highest numbers of juvenile salmon congregate (Beechie et al., 2005). On the Kenai River, restoration efforts have been focused on stream banks that were heavily impacted by boat wakes, dock building, land clearing, and trampling (Dorava and Moore, 1997). To cut down on streambank erosion, light penetrating walkways have been installed in nearly all angler access points on the river on public and private lands, and a large amount of restoration efforts have been completed (ADF&Gb, N.D.; Weiner, 1998). In addition, to cut down on boat pollution and wake erosion special restrictions were put into place; these include limiting boats to have no more than 50 horsepower, four-stroke motors only, no more than 5 or 6 passengers (depending on area), and no more than 21 feet in length and 106 inches wide (ADF&G(c), N.D.). A cost share program was created to help reduce the burden on private individuals to implement these changes (Weiner, 1998).

1.3.2 Tributaries

Tributaries are important for salmon because they greatly increase the amount and diversity of habitat in a watershed. Tributaries are used for salmon spawning and rearing. As mentioned above, the Funny and Killey Rivers are the main spawning habitat used by the Kenai's early-run king salmon (Burger et al., 1985), which are the larger fish that have made the Kenai famous. Another important tributary is the Russian River, which is likely the most popular fishing location in Alaska and is important for sockeye, coho, rainbow trout, and dolly varden (ADF&G, 2020). One indicator for the Russian River's importance over time is archeological evidence of its use by native people dating back approximately 8,000 years (personal communication). Many more king salmon used to inhabit the Russian River; the highest recorded return on record in 1958 was 2,100 kings, but the most recent count in 2004 only totaled 92 kings (Hammarstrom et al., 2007).

1.3.3 Lakes

There are two large, natural lakes on the Kenai River's mainstem—Kenai Lake and Skilak Lake. There are also many lakes in the tributaries of the Kenai, such as Hidden Lake, Upper and Lower Russian Lakes, and Upper and Lower Trail Lakes, to name a few. Lakes are very important for juvenal sockeye, which feed on zooplankton (Schmidt et al., 1995). These nursery lakes are utilized by genetically distinct populations of rearing sockeye (Seeb et al., 2000).

1.3.4 Estuaries

Estuaries are the final type of rearing habitat interviewees mentioned in salmon's migration before they reach the ocean. The length of time salmon spend in the estuaries varies by species. Chinook salmon spend the most time in estuaries (1 to 3 months) and sockeye and pink salmon spend the least (~5 days) (Healey, 1982; Moore et al., 2016). Healy (1982) also identifies important components of estuary habitat and the diverse taxa contributing to salmon's diets while they are there, much of which are detritus feeders. This indicates the importance of detritus in the food web dynamics of estuary habitat.

1.3.5 Food web dynamics

The final important salmon rearing component noted by interviewees was food web dynamics. Research has found that habitat mosaics create important diversity in food webs associated with anadromous fish. For example, the food web dynamics in side channels increases their carrying capacity for anadromous fish to approximately 250% higher than in the main channel (Bellmore et al., 2013). One incredible aspect about salmon is the food web their lifecycle supports. Adult fish transport marine-derived nutrients up rivers and streams where they spawn. After they spawn, they die, leaving their carcasses to be utilized by a host of aquatic and terrestrial species. The dying of salmon enhances the productivity of the system that their offspring are born into, which provides them with food from the time they hatch until they enter the ocean (Kohler et al., 2008; 2012). One issue in many systems is that salmon abundance is far below what it was historically, which has heavily curtailed the transport of marine-derived nutrients inland, which in turn reduces the productivity in salmon rearing habitat (Gresh, Lichatowich, & Schoonmaker, 2000; Kohler et al., 2008; 2012). Dams also disrupt the flow of nutrients up and down watersheds, which can impact both aquatic and terrestrial species (Tonra et al., 2015). Sedimentation, especially in the case of dam removal, can heavily impact invertebrate species utilized by young salmon (Cover et al., 2008). However, researchers have documented shifts in juvenile salmon diets, with the amount of energy they consume equal to what they consumed before the increase in sedimentation (Morley et al., 2021).

1.4 Water Quality

The three main components interviewees identified related to water quality were water temperature, pollutants, and turbidity. Each watershed has its own complex dynamics related to these variables resulting in a range of natural variability. Natural disturbances can disrupt this variability and push conditions outside certain thresholds. Human activity is also a major driver in many watersheds with altered water temperature and flow, pollutants, and turbidity far outside of their natural range; all factors which can jeopardize the salmon that occupy these watersheds. The Kenai is a glacially fed river that also houses two large lakes—Kenai and Skilak—which act as heat sinks, therefore making water temperatures on the Kenai very stable. However, some of the Kenai's tributary streams are more susceptible to fluctuations in water temperature. Pollutants were not a great concern for many interviewees given the remote nature of much of the watershed, but pollutants were mentioned by interviewees in the context of runoff from roads, point source pollution from private properties, and exhaust from boats—much of which was resolved when 2-stroke engines were banned in 2013. Below is a brief overview of how temperature, pollutants, and turbidity effect salmon more broadly.

1.4.1 Temperature

There are many complex dynamics that affect water temperature and flow, these include a host of climatic and geographical factors. Waters in lower latitudes tend to be more vulnerable to high temperatures, and water temperatures of non-glacial systems that are low elevation, have a low gradient, and are rain dominant are quite sensitive to air temperature and precipitation (Lisi et al., 2015; Mauger et al., 2017; Winfree, 2017). During the warmer months of the year, water temperature and flow have an inverse relationship—as flow goes down water temperature goes up. There is a consensus that water temperature exceeding 20°C negatively effects salmon, and the longer salmon are exposed to high temperatures the greater the effect will be (Keefer et al., 2015). Temperatures that fall outside a normal range for a particular salmon population can affect them at all stages of their life cycle (Richter and Kolmes, 2005; Weber-Scannell, 1992). For example, low water levels and high water temperatures can inhibit in- and out-migration, reduce habitat size, and increase mortality at all stages of a salmon's life (Atlas et al., 2021; Jefferies et al., 2014; Marine and Cech, 2004; Singer et al., 2020). In addition, warm water often contains higher concentrations of pathogens which greatly increases the likelihood of infection to fish that are already temperature stressed (Keefer et al., 2015; Taylor, 2021). For an in-depth review of how water temperature affects each species of salmon, see Richter and Kolmes (2005). Schoen and others (2017) also provide a good overview of the variables and conditions that affect stream flow and temperature, and how climate change has and will continue to alter salmon habitat.

1.4.2 Pollutants

There are many sources of water pollution that can threaten salmon. There are naturally released elements that can be toxic to salmon, and concentrations of these elements can increase to harmful levels after natural disturbances like landslides and fires. Naturally occurring pollutants are also released from human activities. For example, copper is neurotoxic to salmon, and is used widely in pesticides, building materials, and vehicle brake pads, and is commonly transported to aquatic systems by stormwater runoff (Davis et al., 2001). Coho salmon are especially sensitive to copper, and even small amounts can affect their olfactory nervous system, which can alter their behavior and homing ability, and high concentrations of copper are lethal (Baldwin et al., 2003; Chapman and Stevens, 1978; McIntyre et al., 2008).

Other types of pollutants like pesticides also enter aquatic systems. Laetz and others (2009; 2013) demonstrated that the mixing of pesticides—conditions that are more likely to occur in watersheds—has a synergistic effect that impact Coho's neurological system which disrupts swimming and feeding behavior. In addition, Landis and others (2019) concluded the combination of high water temperature, low dissolved oxygen, and exposure to pesticides increased the risk of not meeting management goals for chinook salmon populations by 65% to 85% in their study area. Water temperature and dissolved oxygen affect chinook salmon more in the warmer months, and concentrations of pesticides had a greater effect in the winter.

On the Kenai River, many measures of water quality fall within state and federal standards; however, during the summer, a time of intense recreational use, the water quality does decline (Litchfield and Kyle, 1991). Hydrocarbons from boat exhausts, for example, commonly exceed Alaska's state standards in the lower river over this time (Orejuela, 2016). Researchers have shown that during their residency in polluted estuaries, juvenile chinook salmon bioaccumulate substantial levels of toxic chemicals, including extremely high amounts of aromatic hydrocarbons compared to non-polluted reference locations (McCain et al., 1990).

In addition to the direct effects to salmon, pollutants can also affect food web dynamics. EPT testing is a way to measure water quality, which assess the presence or absence of certain sensitive macroinvertebrate species (McCaffrey, 2021). Overall, pollutants can negatively affect salmon directly, and also negatively impact the systems that support them. Therefore, it is critically important to protect aquatic systems from pollutants known to have detrimental effects on the species inhabiting them.

1.4.3 Turbidity

There are some complex dynamics related to turbidity in the Kenai. For example, turbidity reduces the risk of predation of juvenile salmon, which changes their behavior and allows them to occupy more of the available habitat (Gregory, 1993). Turbidity can also increase water temperatures because the suspended sediment absorbs light energy. Increased turbidity in waters already reaching the upper limits of salmon could have negative effects. Turbidity can also decrease light penetration into freshwater lakes and reduce their productivity of zoo plankton and other species utilized by sockeye salmon (Lloyd et al., 1987). Although there can be some negative impacts of increased turbidity, salmon do occupy highly turbid water. The Kenai, Susitna, Kasilof, and Copper rivers are quite turbid but are also highly productive. Increased turbidity beyond its natural range may cause issues for certain populations of salmon.

1.5 Ocean Conditions

The ocean, where salmon spend most of their lives, was described by interviewees as a black box—a dynamic and not well understood place that affects salmon survival and productivity. Interviewees describe a host of attributes that affect salmon, such as ocean temperature, current, acidity, salinity, predation, food abundance, and competition. As difficult as it is to know the dynamics of salmon in freshwater systems, it is vastly more complex to grasp the climactic, environmental, and biological dynamics that affect salmon in the ocean. This notion is echoed by Mantua et al. (1997), stating that it is “the unique life history of salmon, which begins and ends in freshwater streams and involves an extensive period of feeding in the ocean pasture, [that] makes them vulnerable to a variety of environmental changes” (p. 1076). Although the scientific literature gives us some understanding of these dynamics, it sometimes does not provide a clear picture about how each of these attributes affect salmon across different regions and scenarios.

A large amount of work has gone into understanding the dynamics affecting salmon survival and productivity in freshwater systems, with researchers being able to identify linkages between landscapes, rivers, and salmon. However, one question that has been perplexing researchers and managers is the decline and reduced age and size of many salmon species, especially chinook salmon (Lewis et al., 2021; Oke et al., 2020). The reason why this issue is so perplexing is because chinook decline is nearly ubiquitous in all rivers, even pristine rivers that are largely unaffected by humans. Therefore, human impacts to landscapes and rivers is only part of the picture, and we must look to the ocean to understand the causes of this issue. The main problem with this approach is that studying a highly migratory species in the complex, dynamic, and mysterious environment that is the ocean is quite difficult. Therefore, the answer to why chinook salmon are declining everywhere, including pristine systems that are not commercially fished, seems to be the ocean.

1.5.1 Temperature

We do know that there are a host of interactions between climatic, oceanic, and biological variables. One large phenomenon affecting ocean conditions is the Pacific Decadal Oscillation Cycle. In a positive phase, the Gulf of Alaska experiences a warming event, which translates to warmer sea surface temperatures and increased productivity, and the Pacific Northwest experiences a cooling phase. During the positive phases, with warming in the Gulf of Alaska, Mantura et al. (1997) identified increased salmon productivity in Alaska. In a negative cycle, with the warming occurring in the Pacific Northwest, there is an increase in salmon productivity in California, Oregon, and Washington, and decreased productivity in Alaska. Mantura et al. (1997) note these are general trends, and there are more nuanced and complex dynamics occurring within these larger decadal cycles. For example, Mueter et al. (2002) found Alaskan salmon survival increased with ocean warming, however, particular salmon stocks in British Columbia and Washington showed decreased survival rates during warming periods. The authors state these results suggest there are different mechanisms related to ocean temperature affecting survival in the two regions. In addition to these results, different model scenarios produced by Lotze et al. (2019) found not all warming is good, and that climate change will likely cause ocean biomass to decline because of decreased primary productivity. The results of these studies exemplify the complexity in trying to understand how ocean temperature affects salmon productivity.

1.5.2 Acidity

Concentrations of CO_2 are higher than any point during the last 800,000 years (Lüthi et al., 2008), and oceans have absorbed roughly 25% of that CO_2 (Feely et al., 2004; Sabine and Tanhua, 2010). A result of absorbing CO_2 is that the ocean's chemistry has changed. Global surface ocean pH has been reduced by approximately 0.1 units since preindustrial times, which has made the ocean 30% more acidic (Byrne et al., 2010; Feely et al., 2004). Mathis et al. (2015) discuss how ocean acidification may affect commercial and subsistence fishing in Alaska. Thus far, research has shown the effects of ocean acidification mostly affect calcifying organisms such as mollusks and some species of crab (i.e., red king crab and Tanner crab). There is some evidence ocean acidification will alter ecosystem composition toward dominance by non-calcifying organisms (Hall-Spencer et al., 2008). However, the limited data available suggests ocean acidification has little direct effect on most species of fin fish, including salmon. One particular concern is how ocean acidification may disrupt food web dynamics, resulting in decreased salmon productivity. For example, Aydin et al. (2005) suggest a decline in pteropods could reduce pink salmon productivity. Overall, at this point in time, there is little evidence to suggest that ocean acidification will greatly affect salmon.

1.5.3 Predation

In the ocean, salmon are consumed by a variety of ocean predators including sharks, lampreys, ecothermic fish, and marine mammals (Seitz et al., 2019). Researchers who focus on predator-prey dynamics often call for more focus to be given to predators for declines or stalled recoveries in wild salmon stocks. For example, Seitz et al. (2019) tagged 33 adult chinook salmon from the ocean, and of these, they estimated predation led to the mortality of 22 of them, with salmon sharks being responsible for 14 alone. Beamish and Neville (1995) estimated that lampreys in the Frazier River killed approximately 65% and 25% of the wild and hatchery coho and chinook stocks in 1991, respectively. Chasco et al. (2017) also argue increased production of chinook salmon smolt are not producing increased returns due to the recovery and increased populations of ocean predators, specifically pinnipeds and killer whales, are consuming large amounts of chinook before they can return. They estimate pinnipeds had the largest impact on juvenile chinook while killer whales consumed the largest amount of adult chinook (Chasco et al., 2017). Ocean predators consume salmon, which can have large impacts on specific salmon returns. Actions have been taken to reduce predation, such as harassing or killing ocean predators, but these conversations and actions are extremely contentious and spark complex political, economic, and conservation debates (Danley, 2017).

1.5.4 Competition

Another factor at the forefront of interviewees' minds was competition between natural-origin and hatchery-origin salmon. Because of hatchery-origin salmon, the abundance of pink, chum, and sockeye salmon in the North Pacific Ocean is higher now than at any time since the collection of relatively comprehensive statistics began in 1925 (Ruggerone and Irvine, 2018). Hatchery production of salmon largely began in the 1970s starting in Asia, but North America quickly followed (Ruggerone and Irvine, 2018). The three main species produced in hatcheries are sockeye, chum, and pink salmon. Although some of the hatchery production is focused on coho and chinook salmon, this is a very small proportion of total production. It is also important to note there are different kinds of hatchery production with different intended outcomes. Some hatcheries are located in rivers, and are intended to augment runs or make up for habitat loss from dams, for example. These hatcheries were mentioned by interviewees, albeit rarely. The type of hatchery that was at the forefront of interviewees' minds were those releasing billions of salmon into the North Pacific Ocean solely intended for commercial harvest. These hatcheries, primarily located in Alaska, Japan, and Russia released an annual average of 4.4 billion salmon into the North Pacific between 1990-2015, representing approximately 40% of chum, pink, and sockeye salmon biomass for the region (Ruggerone and Irvine, 2018). These commercial operations, often referred to as ‘salmon ranches,’ involve hatching and rearing juvenal salmon until they are ready to enter the ocean. When ready, salmon are released into the ocean where they will eat, grow, and reach maturity. Once mature, they migrate back to their place of origin— at least most of them—where they are caught by commercial fishers, harvested, processed, and sold in markets. The question of how hatchery-origin salmon are affecting native-origin salmon is, like most aspects related to ocean dynamics, difficult to answer. Researchers have continually found a correlation between the number of hatchery-released fish and the decline in natural-origin salmon size and age at maturity. Looking at 90-years of data, Ruggerone and Irvine (2018) found a strong negative correlation between the number of hatchery-origin salmon and average adult salmon weight and length, specifically finding that weight has gone down with the increase in hatchery fish. Other research has also found correlations between these two factors (see Debertin et al., 2017; Hilborn and Eggers, 2000; Lewis et al., 2015; Ruggerone et al., 2016; Shaul and Geiger, 2016). However, as the director of Fisheries Research of Alaska Department of Fish and Game said to the Board of Fish, “correlation is not causation” (Medred, 2021). Recent research is documenting how interaction between the two variables is more complicated because of several confounding factors (Ward et al., 2017). Oke et al. (2021) found hatchery production alone accounted for only a small amount of the total variance in the declines of adult salmon size; however, pink salmon abundance was the only variable negatively related to salmon body size in chinook, chum, sockeye, and coho salmon. This finding, along with other research, indicates hatchery-origin salmon are likely contributing to density-dependent dynamics in the ocean.

Other dynamics, such as ocean currents and salinity also affect salmon, but the scientific literature is sparse concerning these topics. Overall, there is a lively scientific debate over what effect each of these components have on salmon. All the variables identified by interviewees have some effect, and depending on the time and the area, impact salmon to varying degrees. These individual cases nested withing larger dynamics further complicates our understanding of how the ocean affects salmon survival and productivity and makes predictions concerning these things quite difficult.

2. Resource Units

There are many fish species occupying salmon rivers, and the Kenai River is no exception. The fish interviewees identified fall into two groups: anadromous and freshwater (or resident) fish. The term anadromous refers to fish that are born in freshwater, migrate and spend most of their adult lives in saltwater, then migrate back to freshwater to spawn. Interviewees mentioned six species of anadromous fish: chinook salmon, sockeye salmon, coho salmon, pink salmon, chum salmon, and steelhead. The resident fish interviewees mentioned include rainbow trout, dolly varden, and lake trout. There were other species mentioned by some interviewees, like lamprey for example, but most interviewees focused on the species utilized by commercial, sport, or personal use fishers. Therefore, to keep matters simple, so will I.

One of the many aspects making salmon management difficult is that there are multiple species, and each species has unique characteristics, sensitivities, and life histories. In addition, even within species there are many different populations; even one river can house multiple genetically distinct populations of a single species. For example, in the Kenai there are genetically distinct populations of chinook (Berger et al., 1985) and sockeye (Seeb et al., 2000) that utilize different areas and have different life histories. Teasing out these intricacies can be difficult. The use of genetic information has helped shed some light on these issues. Monitoring efforts targeted at collecting tissue samples across the Northern Pacific Ocean have provided insight into how specific populations migrate. An interesting insight from this monitoring is that a high percentage of chinook salmon caught in the Cook Inlet by sport fishers do not originate from Cook Inlet rivers (ADF&Gd, N.D.). Knowing the individual life histories of each salmon species, and the intricacies within genetically distinct populations, could help provide a better understanding of the issues facing salmon. For example, questions such as why some species of salmon, like sockeye and pink, are doing very well and other species, like chinook and chum, are not, can be better addressed with this knowledge. Below is a brief explanation of the unique characteristics of each species, followed by some of the recent changes in fish abundance and how it has affected the fishery.

2.1 Anadromous fish

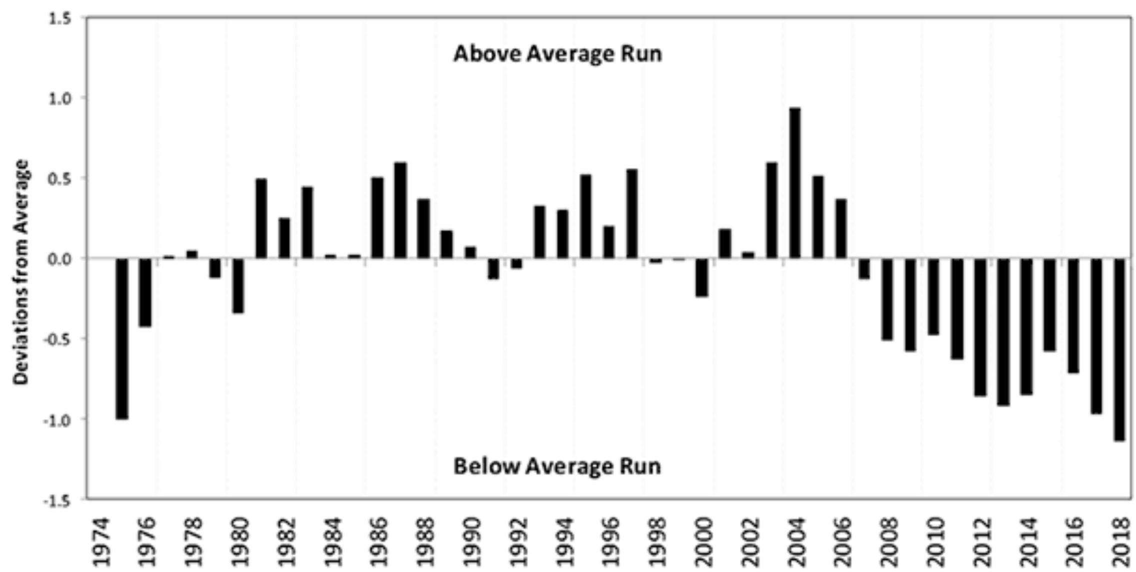
2.1.1Chinook Salmon (Oncorhynchus tshawytscha)

Chinook, or king, salmon are the largest species of Pacific salmon. They average around 86 cm in length and often exceed 13 kg, but chinook salmon have been known to get much larger. The largest chinook salmon on record was caught by commercial fishers in southeast Alaska, which weighed over 57 kg. The largest chinook caught on rod and reel was in the Kenai River in 1985, which weighed 44 kg. There is a large amount of size variability within chinook salmon, and the diversity in size comes from the time they spend in the ocean, which ranges from one to seven (or more) years. Chinook from the same population vary in the amount of time they spend in the ocean, and female chinook are usually older than males when they reach maturity (ADF&Ge, N.D).

One of the primary concerns, if not *the* primary concern, of interviewees was the alarming state of chinook salmon. This phenomenon is not isolated to just the Kenai, as chinook returns across Alaska have been coming in below average since 2007 (Figure 1; ADF&Ge, N.D.). Just in the Kenai, there are two distinct populations of chinook salmon: the early-run and the late-run (Burger et al., 1985). The early-run is comprised of fewer chinook, but they are larger on average, and the late-run is comprised of more, but smaller, chinook. The size of each run has varied significantly over time. Data from 1986 show the early-run has fluctuated between 3,000 to 20,000 spawning chinook, and the late-run has fluctuated between 11,000 and nearly 70,000. Since these data have been collected, late-run chinook had consistently reached their escapement goals until 2010. Since 2010, chinook have frequently come in below their escapement goal, including the last three years: 2019, 2020, 2021 (ADF&Gd, N.D.). The early-run have frequently missed escapement goals since 1986. Fears around the low escapement of early-run chinook sparked management action, and a great deal of work went into improving

Figure A.1.

Kenai River Chinook Runs from 1974-2018



habitat in the Kenai River watershed (Weiner, 1998). These efforts seemed to have a positive impact because runs improved between the year 2000 and 2009, but then fell again. Since 2009, both early- and late-run chinook have had low returns.

In addition to low returns, the size of chinook has also been declining; however, this phenomenon is also not isolated to the Kenai (Lewis et al., 2015; Oke et al., 2021). The primary reason for the size decline is that chinook, and other Pacific salmon, are not spending as much time in the ocean as they used to. There are several theories for why this is the case, including competition with hatchery-origin salmon, predation, harvest, and ocean food web dynamics, to name a few, but researchers have not been able to isolate one cause, and some research (e.g., Oke et al., 2021) has found that all factors seem to play a role in the decline of returning mature salmon. Another issue that researchers are starting to uncover is the loss in chinook genetic diversity. Looking at the

DNA from chinook bones dating back 7,000 years, researchers have estimated that chinook in the Columbia River Basin have lost two-thirds of their genetic diversity since the introduction of euro-Americans in the 1800s (Johnson et al., 2018).

Losing any species is alarming, but the decline in chinook is particularly alarming and tangible because they are very ecologically, economically, and culturally valuable. Although they make up a small proportion of the commercial harvest, they bring a high price because of their high-quality meat. Their largest economic contribution comes from the sport fishery, where many people come to catch a fish of a lifetime. The two factors that make chinook a valued sport fish are their size and their willingness to take an angler's bait, lure, or fly. Once sockeye enter the river, they very rarely bite, so anglers resort to essentially snagging them in the mouth with a technique called 'lining.'

2.1.2 Sockeye Salmon (Oncorhynchus nerka)

Sockeye salmon are the third most abundant species of Pacific salmon, following pink and chum. Some runs in Alaska exceed 10 million fish. Sockeye are the primary target of the commercial and personal use fisheries in the Upper Cook Inlet, and many commercial fisheries around Alaska. The reason sockeye are sought after is because they are abundant and have high-quality meat which stays firm and stores well. Pink and chum meat is considered lower quality because it softens relatively quickly. The average sockeye is around 61 cm in length and 2.7 kg. The largest sockeye on record was over 78 cm in length and weighed 7 kg. Sockeye are primarily filter feeders and feed on zooplankton, but they also occasionally eat small crustations and fish. They spend varying amounts of times in fresh and salt water. Sockeye that are born into river systems with lakes tend to spend more time in fresh water—up to four years—but sockeye in rivers without lakes migrate to the ocean much faster—sometimes in one year. Once in the ocean, they spend one to three years until they reach maturity. A female sockeye can carry between 2,000-5,000 eggs, and depending on the population, they spawn in different habitats, including rivers, tributaries, and lakes (ADF&Gg, N.D.).

Despite the many populations of sockeye in the Kenai River, only two "runs" are counted and reported during their migration—the early-run and the late-run. Attempting to quantify each population would be incredibly difficult, and is likely unnecessary to meet management goals. Many of the early-run sockeye migrate up the Russian River, where they are counted above Russian River Falls. Once fish have made it past the falls, they have escaped the commercial, sport, and personal use fisheries. The escapement goal for early-run sockeye is between 22,000 to 42,000, and the annual average over the last decade is 38,787 (this average excludes the 2019 escapement, which was an outlier with 125,942 sockeye). The in-river goal for the Kenai late-run sockeye is between 700,000-1,400,000, and the annual average over the last decade of in-river late-run sockeye is 1.59 million. The term "in-river" refers to the number of fish that escape the commercial fishery and make it to the river. These fish are still harvested by sport fishers, so sport fishing harvest needs to be subtracted to get an estimate of actual sockeye escapement.

Although it is impossible to get a completely accurate count of sockeye returning to the Kenai River, it is possible to get a close estimate. There are three different measurements to determine sockeye abundance, which include total run, in-river, and escapement. The total run is all the fish that are returning from the ocean to spawn. The total run is difficult, if not impossible, to estimate because the amount harvested by commercial fishers includes a mixed stock (meaning ocean fish originate from different locations). Methods have gotten better to determine where commercially harvested fish are headed, but they are still estimates. The in-river goal is the total run minus commercial harvest. In-river fish are measured in various ways, such as weirs or sonar, and the Kenai uses a sonar. Alaska has a well-developed fish counting program, and many fish counts are updated daily. Anglers regularly check counts to determine where abundance is high to increase their odds. The last measurement is escapement, which is the number of fish that escape the fishery and spawn. This is done by subtracting the sport fishing harvest from the in-river count. Sport fishing harvest is measured by conducting creel surveys.

2.1.3 Coho Salmon (Oncorhynchus kisutch)

Coho salmon are a highly valued sport fish because of their aggressive nature, but they are also caught by commercial and personal use fishers. Their average weight is 3.5 to 5.5 kg, they range between 61 to 76 cm, and the Alaska state record weighed 11.8 kg. Their abundance is quite low compared to sockeye, and no data are published regarding their abundance in the Kenai River. In the Upper Cook Inlet, they are the second most frequently caught sportfish; however, they still comprise a low percentage of the total catch.

Unlike most salmon that rear primarily in freshwater, some juvenile coho transition between brackish estuarine ponds and freshwater during different parts of the season. Juveniles spend one to three years in streams, and up to five years in lakes, before migrating to the ocean. Once in the ocean, the time they spend varies, but most spend approximately 18 months before returning to spawn. In freshwater, coho primarily feed on insects and plankton, and once they enter the ocean they eat fish and squid. (ADF&Gh, N.D.).

2.1.4 Pink Salmon (Oncorhynchus gorbuscha)

Pink salmon are the smallest Pacific salmon, but they are the most abundant. They average between 1.6 – 2.3 kg and are 50 – 64 cm in length. Pink salmon have the shortest life history of all the Pacific salmon, reaching full maturity in only two years. Because of their two-year life cycle, odd- and even-year pinks never crossbreed. This cycle also creates places with dominant runs, where one year—either an odd or an even—will have a more abundant return. However, this does not apply to all spawning habitats. Odd- and ever-year returns are genetically distinct from one another because their short life cycle does not allow intergenerational breeding ADF&Gi, N.D.).

As soon as pink salmon hatch, they migrate to the ocean. Once in the ocean they primarily feed on plankton, small fish, squid, small crustations, and aquatic insects. After spending only 18 months in the ocean, they migrate back to spawn. Pink salmon primarily spawn in the lowest sections of rivers, rarely traveling more than 40 miles upstream. Some even spawn in the estuaries, never fully entering freshwater. However, there are a few populations that make long migrations, but not nearly as far as other salmon species like sockeye and chinook, which can swim over 1,600 km upstream to reach their spawning grounds. In the ocean, they spend a lot of their time close to shore, but they do travel to deeper offshore waters. One very unique characteristic of spawning pink salmon is the large humped back males develop, which has given them their other name "humpies."

The range of pink salmon primarily consists of the northern Pacific Ocean, above the Puget Sound in Washington. As mentioned above, pink salmon are the most abundant salmon in Alaska, and their populations are stable. Billions of commercially released hatchery pink salmon also largely contribute to a high ocean abundance.

Although pink salmon are important for the commercial fishing industry, they are not a valuable sportfish. Commercial fishers have harvested and canned pink salmon in Alaska since the late 1800s. There are currently commercial fisheries for both hatchery-origin and natural-origin pink salmon. The massive number of hatchery-origin pink salmon has raised concerns about their effect on other, natural-origin salmon species. Researchers have found correlations between hatchery pinks and low salmon body weight and returns. This suggest density dependent dynamics are taking place in the ocean, affecting wild salmon stocks (see section 1.5.4 for more information).

From 2013-2015, Prince William Sound runs of pink salmon ranged from 50-142 million and chum ranged from 2.3-5.4 million. The proportion of hatchery pink salmon ranged from 55-86% of the total run and chum ranged from 51-73%. Even though a large amount of hatchery fish are harvested commercially, an estimated 0.8–4.5 million hatchery Pink Salmon and 30,000–90,000 hatchery Chum Salmon strayed into Prince William Sound spawning streams (Knudsen et al., 2021).

2.1.5 Chum Salmon (Oncorhynchus keta)

Chum salmon are the most widely distributed, and second largest Pacific salmon. The Alaskan state record weighed 14.5 kg. Like pink salmon, chum salmon have relatively short river migrations compared to other Pacific salmon, and spawn in the lower reaches of rivers and streams. A small number of populations do, however, migrate far upriver—like in the Yukon River—traveling over 2,000 miles.

There are two general runs of chum in many Alaskan rivers—summer chum and fall chum. Once hatched, they usually start their migration to the ocean within days. Once they reach the ocean, they spend a few months near shore, and then migrate to deeper waters. Chum grow rapidly, generally exceeding 5.4 kg in three to four years. Juvenile chum feed on crustations, insects, and herring. While at sea, adult chum feed on copepods, tunicates, mollusks, and a variety of fishes.

Chum are considered the least desirable salmon species by many, but they are highly prized traditional food in northern Alaska and Asia. The hatchery production of chum salmon for Asian markets started in the 1970s, and the commercial harvest in Alaska quickly doubled, most of which was exported.

Chum in the lower-48 have experienced drastic declines, and the status of chum in Alaska is mixed. As of this writing, many of the western Alaska chum stocks are in decline. The Yukon River, for example, is experiencing a catastrophically low return, and restrictions on all fishing, even subsistence fishing, have been implemented. Along with pink salmon, there are large commercial hatchery programs that produce chum salmon, but hatchery chum are listed as a threat to wild chum by Alaska Department of Fish and Game (ADF&Gj, N.D.)

2.1.6 Steelhead (Oncorhynchus mykiss)

Of the anadromous fish, steelhead are the most unique. Unlike salmon, steelhead do not die after spawning, and can therefore spawn multiple times during their lives. There is no detectible genetic difference between steelhead and rainbow trout; steelhead are anadromous rainbow trout. What makes steelhead different than rainbow trout is that they leave their natal rivers and undergo long ocean migrations until they return to spawn. Once they spawn, and if they survive, they then return to the ocean (ADF&Gk., N.D.).

The major differences between rainbow trout and steelhead come from their life histories. Because steelhead spend large amounts of time in the ocean, they grow larger than rainbow trout. The largest steelhead caught in Alaska was over 19 kg.

Although they are highly prized, few anglers target steelhead in the Kenai River. Other rivers, many of which are located in southeast Alaska, are far more prominent steelhead fisheries. As one interviewee said, "we don't like to talk about our steelhead." What was meant by that statement is that all other species in the Kenai are heavily targeted by resident and non-resident anglers. The steelhead are not, and many people want to keep it that way.

3. Resource Users

Interviewees identified three main groups of resource users: commercial fishers, sport fishers, and personal use fishers. There is a great deal of diversity within each of these three groups. For example, just within the commercial fishing sector, interviewees identified set netters, drift netters, seiners, and trawlers. Each group is named after the method they use to catch fish. These groups also generally fish in different areas, have different harvest rates, and harvest a different composition of species. Within sport fishing, interviewees identified both marine and river anglers; interviewees also made distinctions between guided and non-guided anglers. The metrics used to measure the amount of sport fishing, their success rate, and the amount of fish they harvest are effort, catch, and harvest. These data are collected various ways and are reported by the Alaska Department of Fish and Game. The last distinct group interviewees identified were the personal use fishers, which includes dipnet fishers, a tribal educational fishery, and a small federal subsistence fishery.

Each group of resource users have unique characteristics. For example, the areas they fish, the tactics they use, and their motivations all vary to some degree. However, each of these three groups see great value in their activity, and all contribute quite substantially to the culture and economic well-being of the region. They also contribute to the harvest of salmon. And given that salmon are a limited resource, there is a long, complex history of conflict between these groups—mostly between commercial and sport fishers. Much of this conflict, especially recently, revolves around the poor state of chinook salmon. The decline of chinook populations has led to a deep divide between these groups. Below is a general description of each group's composition, their harvest rates, and some of the unique factors that define them.

3.1 Commercial fishers: Seiners, Drift Netters, Set Netters and Trawlers

3.1.1 Seiners

Seining (also called purse seining) consists of using a large, long net with floats attached to the top. This net is strung out from a boat which creates a wall of net. The net is then drawn into a circle to capture fish. The unique characteristic of saining is that to keep the fish from swimming down and escaping out the bottom, the bottom of the net is pulled together closing it off. This makes the net inescapable. Once the fish are encapsulated by the net, the net is drawn in, consolidating the fish within, which are then brought aboard the fishing vessel. Permits for seining are only given in the Lower Cook Inlet (Strong, 2018). The three main species targeted by seiners are pink salmon (45.1%), sockeye (36.1%), and chum (17.2%). Only a small portion of the seiner's catch contains chinook (0.1%) and coho (1.5%) salmon.

3.1.2 Drift Netters

Drift netters operate in the Upper Cook Inlet. Drift netting consists of running out long gill nets from boats. These nets float on the top and drape down into the water. After the nets drift in the water, one end of the net is picked up and the entire net is pulled back into the boat. Because this is a gill net, the fish that swim into the net are caught in the net's mesh, usually just behind the gills. The drift net fleet primarily targets sockeye, which is 84% of their catch. However, they also catch chum (10%), coho (4%), pink (1.4%), and chinook (0.2%) (Strong, 2018).

3.1.3 Set Netters

The set net fishery primarily operates in the Upper Cook Inlet, but there are a few permits that operate in the Lower Cook Inlet. Set netters operate in fixed locations in the ocean near the shoreline. This method consists of stringing gill nets between two fixed points and letting them sit. Then a relatively small vessel pulls the nets and removes the fish caught in them. The primary target of set netters are sockeye, which consist of 86.6% of their catch. They also catch coho (5.9%), chinook (3.9%), pink (2.1%), and chum (1.5%) (Strong, 2018). Set netters catch the largest proportion of chinook salmon out of the commercial fishers, and given the poor state of chinook, set netters are often at the center of conflict and regulatory measures geared toward increasing chinook escapement.

3.1.4 Trawlers

Trawlers do not directly target salmon but were included by interviewees because of their bycatch—which is when fish are caught by accident while actively trying to catch another species (Liller and Howard, 2017). In many cases, bycatch cannot be sold so it is donated to food banks. The trawler fishing industry operates throughout the North Pacific Ocean, primarily targeting pollock (*Gadus chalcogrammus*), a fish commonly used for fish sandwiches and imitation crab meat. In 2020, commercial fishers landed 3.23 billion pounds of pollock that was valued at $420 million (NOAA, N.D.). The method utilized by pollock fishers is midwater trawling, which consists of pulling a large cone-shaped net through the water, which is intended to rarely encounter the sea floor, reducing habitat damage. The pollock fishery is also considered by the National Oceanic and Atmospheric Administration as one of the best managed fisheries in the world. It is estimated that less than 1% of the fisheries total catch is considered bycatch; however, the bycatch of salmon—specifically chinook salmon—is still an area of concern. The amount of chinook bycatch from trawling, since 1991, has ranged from 8,200 in the year 2000 to over

130,000 in 2007 (Liller and Howard, 2017). Since the alarmingly high catch in 2007, new regulations were implemented to reduce bycatch, and ever since annual bycatch of chinook in the Bering Sea and Aleutian Islands has ranged from 12,000 to 33,000 (Liller and Howard, 2017). To better understand chinook salmon bycatch, the North Pacific Observer Program was initiated in 2005. The goal of this program is to systematically collect tissue samples from chinook salmon bycatch to identify the different stocks and the general region of origin of the chinook salmon (Faunce, 2015). The findings of this effort illustrate the large range some salmon stocks cover. The Observer Program data has identified chinook salmon caught in the Bering Sea originated from Alaska, British Columbia, and all three states (California, Oregon, and. Washington) of the West Coast (Guthrie, Nguyen, and Guyon, 2014). Additional efforts were implemented in 2016 to further reduce salmon bycatch, which included using bycatch rates to identify salmon hotspots and closing those to pollock fishing and installing salmon excluding devices on the trawling nets (these are still being tested to determine their effectiveness). The areas in which bycatch occurs illustrates that salmon, with their long migrations and complex life cycles, are acted upon, intentionally and unintentionally, by many variables, which has an impact on salmon health and abundance.

All of the commercial fishing takes place in the ocean, and commercial fishers harvest the largest number of salmon. Since 2000, commercial fishers in the Upper Cook Inlet harvested around 2.5 to 5 million salmon each year. In comparison, sport fishers harvested roughly 425,000 salmon per year, and personal use fishers—which is growing in popularity—has increased its harvest from roughly 200,000 to 450,000 salmon since 2000 (Schoen et al., 2017).

3.2 Sport Fishing

Sport fishing is the next distinct group of resource users identified by interviewees. Within the broad group of sport fishing, interviewees made a distinction between marine and river sport anglers and guided and non-guided anglers. Most of the sport fishing for salmon takes place in rivers where fish are more concentrated and accessible. Targeting salmon in the ocean is more difficult and takes more specialized equipment, like an ocean faring boat. Interviewees also differentiated between guided and non-guided anglers because of the success rates, equipment used (e.g., boats), and species targeted often differ between these two groups. For example, the lower Kenai supports a large guiding community that specializes in targeting chinook salmon. The method used is back trawling, which requires a boat. Because of its status of having the largest chinook in the world, many people travel to the Kenai to fish for them. Given the tactics used, most people who come to fish for chinook hire a guide with a boat. Many non-guided anglers on the lower Kenai target sockeye because they are easily caught from shore. Because of the low returns of chinook, many guides who started their careers solely focused on chinook and coho now spend a large portion of their time fishing for sockeye. On the upper Kenai, many of the guided anglers fish for trout and dolly varden, and most of the non-guided anglers fish for sockeye.

3.3 Personal Use Fishers: Dip Netters, Subsistence Fishers, and the Kenaitze

The last group identified by interviewees was personal use fishers. The main goal of personal use fishing is to provide food for Alaskan residents. Two of the main differentiating characteristics between personal use and sport fishing is that they use tactics that optimize catch—dip nets, set nets, etc.—and personal use fishers are completely harvest focused. The thing that differentiates personal use fishers from the commercial fishers are the areas they fish and what they catch cannot be sold—it is intended for personal use only. The three subgroups within personal use fishers are dip netters, subsistence fishers, and the Kenaitze educational fishery. As a result of the Kenai Fish Wars—a long and contentious fight between commercial, sport, and subsistence fishers—the state banned "subsistence fishing" from much of the Upper Cook Inlet and the Alaska Board of Fisheries adopted the "personal use" fishery in its place in 1996 (Sechrist and Rutz, 2014). The primary target of the dipnet fishery is sockeye, but other species are sometimes harvested. The personal use dipnet fishery is only available to Alaskan residents, and to participate residents need to obtain a free permit which is designed to help the Alaska Department of Fish and Game estimate participation and harvest. Personal use fishers are allowed to harvest a total of 25 salmon, with an additional ten salmon for each member of the permit holder's household. Therefore, given the regulations, a family of four can harvest 55 salmon per year.

There are a few lingering federally managed "subsistence" fisheries still present on the Kenai. Currently, there are three communities with "rural" determination that qualify for federal fisheries on the Kenai: Hope, Cooper Landing, and Ninilchik. Primarily the harvest is comprised of sockeye taken from the Russian River and mainstem Kenai River. The methods and means include dip nets, rod and reel, and a gillnet fishery. Most of the fish are taken by dip net at the Russian River Falls and the remainder in the lower Kenai River via gillnet. The harvest is slowly increasing but ranges between 3,000 to 5,000 fish annually (personal communication). The community of Moose Pass was recently determined rural, but they have not applied for a permit to participate in the subsistence fishery as of late 2021. A few species other than sockeye are harvested, mostly coho, but they are primarily incidental catch and are very minimal.

The last fishery in the personal use category is the Kenaitze educational fishery. The Kenaitze people have been harvesting salmon from the Upper Cook Inlet for thousands of years. Through a long legal process the Kenaitze Tribe was granted permission by the state of Alaska to deploy one “educational” net. This net, among the thousands present in the Upper Cook Inlet, is specifically designed to provide food for tribal members and a way to connect youth to the process of harvesting and processing salmon. The Kenaitze tribe holds summer fish camps with curriculum focused on traditional fishing methods, identifying salmon species, and cleaning and preserving fish for winter (Kenaitze, N.D.). In addition, members of the Kenaitze Tribe can reserve times to use the net to harvest their own salmon.

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CURRICULUM VITAE

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SHORT BIO

Chase C. Lamborn is the Assistant Director of Outreach and Education for the Institute of Outdoor Recreation and Tourism and a PhD student in the Department of Environment and Society. Chase has been working within the Institute since 2010, and became a Research Associate after completing a master's degree in 2014. Chase has also worked for the USDA Forest Service collecting fisheries data in the Pacific Northwest and managing recreation in southeastern Utah. Chase earned his bachelor's degree in Recreation Resource Management and a master's degree in Human Dimensions of Ecosystem Science and Management. Off-campus, Chase is an avid rock climber and fly angler.

SCOPE OF RESEARCH

Most of Chase's work has used social science tools to explore the recreational use and management of public lands. He has specifically focused on gathering information used to inform management actions that seek a balance between protecting resources and providing high quality recreation experiences. In addition, Chase is interested in merging social, ecological, and climate science to better understand and sustain highly valued, yet vulnerable resources that support recreation activates that rely on healthy, functioning ecosystems.

EDUCATION

Utah State University — Environment and Society — PhD (2022)

Utah State University — Human Dimensions of Ecosystem Management and Science — MS (2014)

Utah State University — Recreation Resource Management — BS (2010)
- Undergraduate Teaching Fellow of the Year Award
- Distinguished Service Member Award
- Outstanding Senior of the Year Award

PROFESSIONAL APPOINTMENTS

2021 – Assistant Director of Visitor Use Monitoring and Management, Institute of Outdoor Recreation and Tourism
Utah State University, Department of Environment and Society
- Coordinate the Institute's visitor use monitoring research, which includes designing survey instruments and sampling methods, overseeing data collection, managing and analyzing data, writing reports and journal articles, and presenting findings. Duties also include coordinating field work and managing staff, teaching, and assisting graduate students.

2019 – 2021 Assistant Director of Outreach and Education, Institute of Outdoor Recreation and Tourism
Utah State University, Department of Environment and Society
- Coordinate the Institute's research, which includes designing survey instruments and sampling methods, overseeing data collection, managing and analyzing data, writing reports and journal articles, and presenting findings. Duties also include managing employees and teaching.

2014 – 2019 Research Associate, Institute of Outdoor Recreation and Tourism

Utah State University, Department of Environment and Society

- Coordinate the Institute's research, which includes designing survey instruments and sampling methods, overseeing data collection, managing and analyzing data, writing reports and journal articles, and presenting findings. Duties also include managing budgets, employees, contracts, and schedules.

2013 – 2013 Recreation Technician, Moab-Monticello Ranger District
USDA Forest Service

- Managed recreation, which included maintaining campgrounds, water systems, travel management plans, and signage. Duties also included collecting fees as a certified Collection Officer, enforced Forest regulations, and constructed kiosks, road barriers, and fences.
- Type 2 Firefighter and B Feller (Region 4).

2012 – 2013 Project Manager, Institute of Outdoor Recreation and Tourism Utah State University
Department of Environment and Society

- Coordinated the 2011-2012 National Visitor Use Monitoring Program for the Uinta-Wasatch-Cache National Forest.
- Duties included overseeing employees, fleet vehicles, budgets, schedules, survey equipment, data collection, and data quality control.
- Managed a $147,000 budget; adhered to a strict survey schedule; surveyed hundreds of sites throughout the Uinta-Wasatch-Cache National Forest in all months of the 2011-2012 survey year; and oversaw the completion of over 3,300 visitor surveys.

2011 –2011 Recreation Technician, Moab-Monticello Ranger District USDA Forest Service

- Managed an eight-person youth corps to complete various projects, including trail building and maintenance, invasive species removal (tamarisk), and fence construction (pole-and-rail and barbed wire).
- Lead four to eight-day backcountry trips, often in the Dark Canyon Wilderness area.
- Worked with various groups, including Forest Service personnel, Wilderness Volunteers, and the Canyon Country Youth Corps to complete trail, invasive species removal, and fencing projects.

2010 – 2011 Research Assistant, Institute of Outdoor Recreation and Tourism, Utah State University

Department of Environment and Society

- Coordinated research, which included managing data collection, conducting interviews, data analysis, and reporting findings.
- Conducted social science data collection, analysis, and reporting for the Forest Service and the Bureau of Land Management.

2009 – 2009 Biological Technician, U.S. Rocky Mountain Research Station USDA Forest Service

- Collected data for an ongoing research project that is examining steelhead (Oncorhynchus mykiss) and bull trout (Salvelinus confluentus) habitat in the Columbia River Basin.
- Received 160 hours of training on data collection methods, safety, first-aid, driving, Leave-No-Trace, fluvial geomorphology, ecology, threatened and endangered species, and the impacts of invasive species.
- Worked eight-day hitches throughout the summer in remote areas (including Wilderness) in Oregon, Washington, Idaho, and Nevada.
- Enhanced personal skills in map reading, GPS use, map drawing, and navigation in remote areas. Followed strict data collection protocols. Gained knowledge and understanding of how different land uses and natural disturbances affect stream quality and habitat.

SCHOLARSHIP

PUBLICATIONS:

PEER REVIEWED ARTICLES (PUBLISHED AND IN PRESS)

1. Smith, J. W., Miller, A. B., **Lamborn, C. C.**, Spernbauer, B. S., Creany, N., Richards, J. C., Meyer, C., Nesbitt, J., Rempel, W., Wilkins. E. J., Miller, Z. D., Freimund, W., & Monz, C. (2021). Motivations and spatial behavior of OHV recreationists: A case-study from central Utah (USA). *Journal of Outdoor Recreation and Tourism,* 36, 100426.

2. **Lamborn, C. C.** & Smith J. W. (2019). Human perceptions of, and adaptations to, shifting runoff cycles: A case study of the Yellowstone River (Montana, USA). *Fisheries Research,* 216, 96-108.

3. Ceurvorst, R, L., & **Lamborn, C. C.** (2018). Visitor attitudes and value orientations for a proposed national monument. *Journal of Outdoor Recreation and Tourism*, 23, 33-43.

4. Smith, J. W., Wilkins, E., Gayle, R., & **Lamborn, C. C.** (2018). Climate and visitation to Utah's "Mighty 5" national parks. *Tourism Geographies,* 20, 250-272.

5. **Lamborn, C. C.**, Smith, J. W., & Burr, S. W. (2017). User fees displace low-income outdoor recreationists. *Landscape and Urban Planning*, 167, 165-176.

PUBLICATIONS:

PEER REVIEWED ARTICLES (IN PREPARATION)

1. **Lamborn, C. C.** & Smith J. W. (in prep). A social-ecological framework for salmon fisheries: A case study of the Kenai River fishery (Alaska, USA).
2. **Lamborn, C. C.** & Smith J. W. (in prep). Assessing the potential long-term social and ecological impacts of fire to the Kenai River fishery.

TECHNICAL AND PROJECT REPORTS

1. Furr, G., **Lamborn**, C., Sisneros-Kidd, A., Monz, C., & Wesstrom, S. (2019). Backcountry Visitor Experience and Social Science Indicators for Glacier Bay National Park & Preserve. Natural Resource Report. National Park Service, Fort Collins, Colorado.

2. Smith, J. W., & **Lamborn, C. C.** (2017). *The economic impact of snowmobiling in Utah*. Logan, UT: Institute of Outdoor Recreation and Tourism, Department of Environment and Society, Utah State University.

3. **Lamborn, C. C.**, Burr, S. W., & Nelson, R. (2016). *Dalton Wells and Willow Springs Visitor Use Study*. Logan, UT: Institute of Outdoor Recreation and Tourism, Department of Environment and Society, Utah State University.

4. **Lamborn, C. C.**, Burr, S. W., & Lofthouse, J. (2016). *Pleasant Grove Visitor Use Study: Follow-up survey report.* Logan, UT: Institute of Outdoor Recreation and Tourism, Department of Environment and Society, Utah State University.

5. **Lamborn, C. C.**, Burr, S. W., & Lofthouse, J. (2016). *Pleasant Grove Visitor Use Study: Winter quarterly report.* Logan, UT: Institute of Outdoor Recreation and Tourism, Department of Environment and Society, Utah State University.

6. **Lamborn, C. C.**, & Burr, S. W. (2016). *Estimation of visitor use Little Cottonwood, Big Cottonwood, and Millcreek Canyons.* Logan, UT: Institute of Outdoor Recreation and Tourism, Department of Environment and Society, Utah State University.
7. **Lamborn, C. C.**, Burr, S. W., & Lofthouse, J. (2015). *Pleasant Grove Visitor Use Study: Fall quarterly report.* Logan, UT: Institute of Outdoor Recreation and Tourism, Department of Environment and Society, Utah State University.
8. **Lamborn, C. C.**, & Burr, S. W. (2015). *Central Wasatch Visitor Use Study: Ski area report.* Logan, UT: Institute of Outdoor Recreation and Tourism, Department of Environment and Society, Utah State University.
9. **Lamborn, C. C.**, Burr, S. W., & Lofthouse, J. (2015). *Pleasant Grove Visitor Use Study: Summer quarterly report.* Logan, UT: Institute of Outdoor Recreation and Tourism, Department of Environment and Society, Utah State University.
10. **Lamborn, C. C.**, Burr, S. W., & Lofthouse, J. (2015). *Pleasant Grove Visitor Use Study: Spring quarterly report.* Logan, UT: Institute of Outdoor Recreation and Tourism, Department of Environment and Society, Utah State University.
11. **Lamborn, C. C.**, Burr, S. W., Kessler, B., & Kim, M. (2015). *Central Wasatch Visitor Use Study: Follow-up survey report.* Logan, UT: Institute of Outdoor Recreation and Tourism, Department of Environment and Society, Utah State University.
12. **Lamborn, C. C.**, Burr, S. W., & Kessler, B. (2015). *Central Wasatch Visitor Use Study: Spring quarterly report.* Logan, UT: Institute of Outdoor Recreation and Tourism, Department of Environment and Society, Utah State University.
13. **Lamborn, C. C.**, Burr, S. W., & Kessler, B. (2015). *Central Wasatch Visitor Use Study: Winter quarterly report.* Logan, UT: Institute of Outdoor Recreation and Tourism, Department of Environment and Society, Utah State University.
14. **Lamborn, C. C.**, Burr, S. W., & Kessler, B. (2015). *Central Wasatch Visitor Use Study: Fall quarterly report.* Logan, UT: Institute of Outdoor Recreation and Tourism, Department of Environment and Society, Utah State University.
15. **Lamborn, C. C.**, Burr, S. W., & Kessler, B. (2015). *Central Wasatch Visitor Use Study: Summer quarterly report.* Logan, UT: Institute of Outdoor Recreation and Tourism, Department of Environment and Society, Utah State University.
16. Burr, S. W., Reiter, D., **Lamborn, C. C.**, Hull, T., & Zeitlin, J. (2011). *Baseline information for outfitters and guides needs assessments in USFS Region 4: Final report.* Logan, UT: Institute of Outdoor Recreation and Tourism, Department of Environment and Society, Utah State University.

THESIS

Lamborn, C. C. (2014). *Exploring visitor attitudes toward the proposed Greater Canyonlands National Monument: A survey in Utah's Indian Creek Corridor*http://digitalcommons.usu.edu/etd/40/. Logan, UT: Utah State University. Committee: Robyn L. Ceurvorst (chair), Steven W. Burr, and Steve Daniels.

PRESENTATIONS:

1. Lamborn, C. C., (November, 2021). A social-ecological framework for understanding salmon fisheries. Basecamp Conference, Tucson, AZ.

2. Lamborn, C. C. (2020, August). Central Wasatch Visitor Use Study: A look at capacity. Results presented to the Central Wasatch Commission via Zoom.
3. **Lamborn, C. C.** & Smith, J. W. (2019, October). Impacts of Drought and the Outbreak of Proliferative Kidney Disease on Recreational Angling in the Yellowstone River Watershed. Results presented at the Restoring the West Conference, Logan, UT.
4. **Lamborn, C. C.** & Smith, J. W. (2019, May). Impacts of Drought and the Outbreak of Proliferative Kidney Disease on Recreational Angling in the Yellowstone River Watershed. Results presented at the National Outdoor Recreation Conference, Rapid City, SD.
5. **Lamborn, C. C.** & Smith, J. W. (2018, June). Exploring recent trends in recreational angling in the Intermountain West. Results presented at the International Symposium on Society and Resource Management, Snowbird, UT.
6. **Lamborn, C. C.** & Smith, J. W. (2018, March). Exploring how drought affects recreational angling in the Intermountain West. Results presented at the Spring Runoff Conference, Logan, UT.
7. **Lamborn, C. C.** & Smith, J. W. (2018, March). Exploring how drought affects recreational angling in the Intermountain West. Results presented at the Division of Wildlife Resources State Office, Salt Lake City, UT.
8. **Lamborn, C. C.**, & Smith, J. W. (2017, September). *Climate change and fishing in the Intermountain West.* Paper presented at the Pathways: Integrating Human Dimensions into Fisheries and Wildlife Management Conference, Estes Park, Colorado.
9. **Lamborn, C. C.**, & Burr, S. W. (2016, June). *Central Wasatch visitor use study*. Results presented at the International Symposium on Society and Resource Management, Houghton, MI.
10. **Lamborn, C. C.**, Burr, S. W., Lofthouse, J., & Kessler, B. A. (2016, June). *Pleasant Grove Ranger District visitor use study.* Results presented at the American Fork Vision Executive Board meeting, Highland, UT.
11. **Lamborn, C. C.**, Burr, S. W., Lofthouse, J., & Kessler, B. A. (2016, May). *Pleasant Grove Ranger District visitor use study.* Results presented at Highland City Hall, Highland, UT.
12. **Lamborn C. C.**, & Burr, S. W. (2015, November). *Central Wasatch visitor use study.* Results presented at the Mountain Accord Executive Board meeting, Park City, UT.
13. **Lamborn C. C.**, & Burr, S. W. (2015, November). *Central Wasatch visitor use study.* Results presented at the Salt Lake City Library, Salt Lake City, UT.
14. **Lamborn, C. C.**, & Burr, S. W. (2015, December). *Central Wasatch visitor use study.* Results presented at the Utah Outdoor Recreation Advisory Board meeting, Salt Lake City, UT.
15. **Lamborn, C. C.** & Ceurvorst, R. (2013, September). *Exploring visitor attitudes toward the Greater Canyonlands National Monument: A survey in Utah's Indian Creek Corridor.* Thesis presented at the Biennial Conference of Science & Management on the Colorado Plateau & Southwest Region, Flagstaff, AZ.

MEDIA COVERAGE

STORIES FEATURING EXTENSION AND RESEARCH FROM THE INSTITUTE OF OUTDOOR RECREATION AND TOURISM

Media outlet

Daily Herald

1. Allred, C. (2016, June). Survey shows locals love American Fork Canyon just the way it is. *Daily Herald.*

High Country News

1. Blankenbuehler, P. (2015, December). Two visions for the future collide in the Wasatch Range. *High Country News.*

Idaho Press-Tribune

1. Opsahl, K. (2017, December 19). USU report: Utah snowmobilers decline despite increasing population. *Idaho Press-Tribune.*

London School of Economics USAPP – American Politics and Policy Blog

1. Lamborn, C. C., & Smith, J. W. (2017, October 18). Asking for a fee – even a small one – changes the way people use the outdoors. *London School of Economics USAPP – American Politics and Policy Blog.*

Salt Lake Tribune

1. Maffly, B. (2016, December 24). As snowmobiles lose popularity in Utah, retrofitted UTVs and motorcycles gain more traction. *Salt Lake Tribune.*

Standard-Examiner

1. Larsen, L. (2017, December 22). Snowmobiling on the decline in Utah, but still moves millions through Weber Co. *Standard-Examiner.*
2. Larsen, L. (2017, July 16). Study shows public land user fees leave low-income citizens feeling priced out. *Standard-Examiner.*

U.S. News and World Report

1. Report: Snowmobilers decline despite rising Utah population (2017, December 20). *U.S. News and World Report.*

Utah Public Radio

1. Gayle, R. (2018, July). Loving our lands: Who foots the bill for increasing maintenance backlog? *Utah Public Radio.*

Utah State Today

1. Gilbert, L. (2017, July 10). Small fees for access to public lands changes how some use the outdoors. *Utah State Today.*

AWARDS AND HONORS:

- 2020 Staff Researcher of the Year, Utah State University
- 2016 ISSRM Travel Scholarship recipient, Utah State University.
- 2011 Outstanding Senior of the Year Award, Utah State University.
- 2010 Undergraduate Teaching Fellow of the Year Award, Utah State University.
- 2010 Distinguished Service Member Award, Utah State University

TEACHING

TEACHING EXPERIENCE:

COURSES TAUGHT

Recreation Use Monitoring and Assessment (Utah State University, ENVS 4550/6900) – This field-based course provides experience in monitoring and assessing recreation use impacts. Students use a variety of research methods to collect, analyze, and report various types of recreation-based site impact and visitor use data. Students also spend time in the field with land managers and NGO personnel to gain an understanding of how collaborative partnerships work to maintain, monitor, and restore recreation resources. Upon completion of this course, students have learned the legal and theoretical reasons for managing recreation on public lands; used measuring techniques to collect both biophysical and social data, and analyzed those data into interpretable results with an associated plan of action. 10-14 students. Summer 2012, 2013, 2014, 2015, 2016, 2017, 2018, 2021

Fundamentals of Recreation Resource Management (Utah State University, ENVS 3300) – This course presents students with the fundamental principles of wildland recreation management, which include the following: characteristics of recreation use and users; introduction to planning concepts; management of wildland recreation facilities and infrastructure; and integration with other natural resource uses. This course was taught online to students across the state of Utah. 35 students. Spring 2021.

Recreation Policy and Planning (Utah State University, ENVS 4130) –The course provides an overview of the historical, legal, and political context of outdoor recreation policy on public lands; government agency culture, regulation, and partnering; relationship of outdoor recreation to tourism; and theory and application of principal planning tools for outdoor recreation settings. 35 students. Spring 2020

Wildland Recreation Behavior (Utah State University, ENVS 4500) – This course delves into the interdisciplinary topic of understanding and managing recreation behavior in wildlands. The focus is on using ecological and social science principles and concepts to examine the causes and consequences of human behavior in outdoor recreation areas. The primary goal of the class is to help students learn how to manage outdoor recreation activities for ecological and social sustainability. Upon completion of this course, students will have an understanding of: 1) wildlands and the recreational use that occurs on them; 2) the social and ecological impacts of wildland recreation; and 3) the management strategies that can be utilized to mitigate these impacts. This course was taught in-person and broadcast to multiple satellite campus across the state of Utah. 25 students. Spring 2019.

Outdoor Recreation Management (Utah State University, PRP 2500) – This course provides an introduction to the fundamental principles of outdoor recreation management by exploring the four major elements that comprise an outdoor recreation system: natural environment, human/culture, laws/politics, and the economy. There is an emphasis on commonly used tools and frameworks used by outdoor recreation professionals to manage recreation resources and visitor experience. Students also review and apply course concepts by both participating in and leading outdoor recreation experiences in the field. 20 students. Spring 2017.

TEACHING ASSISTANT

Recreation Policy and Planning (Utah State University, ENVS 4130) –The course provides an overview of the historical, legal, and political context of outdoor recreation policy on public lands; government agency culture, regulation, and partnering; relationship of outdoor recreation to tourism; and theory and application of principal planning tools for outdoor recreation settings. 30-35 students. Spring 2011, 2012, 2013, 2014.

Wildland Recreation Behavior (Utah State University, ENVS 4500) – This course provides an overview of the social, psychological, and geographic influences on human behaviors in wildland recreation settings. Emphasis on critical problems affecting public land recreation management. 30 students. Fall 2013.

PROJECT MANAGEMENT

PROJECTS:

2021-2022 Uinta-Wasatch-Cache National Forest National Visitor Use Monitoring Study: Round Five. USDA Forest Service.

2021-2022 Ashley National Forest National Visitor Use Monitoring Study: Round Five. USDA Forest Service.

2020-2021 Manti-La Sal National Forest national visitor use monitoring study: Round five. USDA Forest Service.

GRANTS

GRANTS:

Smith, J. W., Miller, A. B., **Lamborn, C. C**., Monz, C., & Rivers, E. (2021-2022). Amount: $197,366.49. Central Wasatch Visitor Use Study: Phase 2 (Ecological and Physical Assessments). Central Wasatch Commission.

Smith, J. W., Miller, A. B., **Lamborn, C. C.**, Monz, C., & Rumore, D. (2021). Amount: $37,325. Central Wasatch Visitor Use Study: Phase 1. Central Wasatch Commission.

Smith, J. W., & **Lamborn, C. C.** (2020-2022). Amount: $112,152. 2021 statewide Utah angler survey. Utah Division of Wildlife Resources, Utah Department of Natural Resources.

Smith, J. W., & **Lamborn, C. C.** (2020-2022). Amount: $24,963. Mapping the immediate and prolonged impacts of, and adaptations to, fire in the Kenai River fishery. Joint Fire Science Program Graduate Student Innovation Award.