Participatory modeling to evaluate tribal pinniped harvest in Puget Sound as a tool for salmon recovery

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Abstract

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Pinnipeds and salmon have been actively managed by tribes in the Salish Sea since time immemorial. Tribal pinniped harvest impacted pinniped populations directly through removals, indirectly through disturbance, and spatially by excluding them from frequently utilized areas near village sites, which often included important salmon migration routes. Current management practices struggle to balance pinniped recovery success with the need to protect the threatened salmon populations they prey on. We employed a Participatory Modeling Process to collaboratively develop a modeling framework with treaty tribes in Western Washington that could explore the impacts of pinniped management scenarios on the survival of returning adult salmon in terminal areas. We developed a model that simulates the dynamics between pinnipeds and salmon using a combination of agent-based and dynamic components to represent aspects of pinniped behavior, foraging decisions, fear conditioning, individual learning, and social contagion. Using this model, we explored different management regimes for pinniped harvest and evaluated success by monitoring the number of salmon who survive predation by pinnipeds and are therefore available to fulfill other management objectives. We carried out these simulations in two case study locations: the Ballard Locks in collaboration with the Muckleshoot Indian Tribe, and the Nisqually River in collaboration with the Nisqually Indian Tribe. We found that management scenarios where pinniped management was carried out in a way that allowed pinniped predators to develop fear of management activity were more effective at improving salmon survival. We also identified specific scenarios for each case study that benefitted the specific salmon runs that use those systems and described the general characteristics of successful management strategies. The results from this study will be used by our partners in tribal resource management agencies to structure pinniped management in their Usual & Accustomed areas and identify data gaps for future monitoring efforts. Providing pathways for tribes in Washington to exercise their treaty rights to harvest pinnipeds in a way that mitigates salmon predation hotspots could be an effective management strategy that balances complex conservation objectives while operating within existing legal and political frameworks.

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Chapter 1 Introduction

In heavily modified ecological systems, conflicts frequently arise between management priorities. These conflicts are well illustrated in marine systems where conservation and harvest have been at odds for hundreds of years. Sea otters (*Enhydra lutris*) on the west coast of North America serve as an example of the variety of conflicts that can emerge, including management challenges caused by enforcing protections for both predators (e.g. sea otters) and prey (e.g. endangered abalone species in California), reconciling different stakeholder value types (e.g. economic value of shellfish fisheries and aesthetic value of sea otter presence), and balancing access to resources for users with different legal and cultural standings (e.g. recreational, commercial, First Nations and Tribal fisheries) (Fanshawe et al. 2003; Salomon et al. 2015; Carswell et al. 2015). These conflicts are complex and multifaceted, requiring consideration of a wide range of interdisciplinary impacts. Modeling has emerged as a valuable decision support tool that can help managers weigh management scenarios and evaluate the impact and uncertainty of their actions across a range of ecological, economic, and social aspects (Butterworth et al. 1995; Preikshot 2008; Punt et al. 2016).

Challenges are especially pronounced when managers are tasked with simultaneously conserving prey and predator populations. Many species of marine mammals were extirpated or severely depleted by hunting during the 19th and 20th centuries (Magera et al. 2013). Since then, marine mammals have received widespread protection from direct and indirect human impacts through both international agreements (e.g. International Convention for the Regulation of Whaling) and domestic legislation (e.g. Marine Mammal Protection Act (MMPA) in the United States). While many species of marine mammals still face considerable challenges to their recovery, some pinniped species are reaching their recovery targets (Kovacs et al. 2012; Roman et al. 2013; Erlandson et al. 2019). These pinniped species may be a success story for conservation, but they are also at the forefront of conflict between fisheries and conservation due to the threat they pose to their less recovered prey species and the fisheries that rely on them (Butterworth et al. 1995; Morissette et al. 2012; Nelson 2020). Now these recovering pinniped populations are seen as a nuisance by some marine resource users, and managers are tasked with crafting policies that balance the many facets of their legal mandates.

The three most common pinniped species of the Puget Sound – Steller sea lions (*Eumetopias jubatus*), California sea lions (*Zalophus californianus*), and harbor seals (*Phoca vitulina*) – have increased in abundance since the implementation of the MMPA in 1972, and harbor seal and California sea lions populations are believed to be fluctuating near carrying capacity (Jeffries et al. 2003; Wiles 2015; Laake et al. 2018; Jefferson et al. 2021; Pearson et al. 2024). Researchers and managers hypothesize that predation by these recovered pinniped species is a barrier to the recovery of protected salmon in the region (Brown et al. 1997; Lessard et al. 2005; Trites and Rosen 2019; Trzcinski 2020; Washington State Academy of Sciences 2022). Pinniped predation on salmon has been documented at most large river mouths in the Pacific Northwest (Brown et al. 1997; Wright et al. 2007; Scordino 2010; Berejikian et al. 2016) and recent modeling exercises have linked regional abundance of harbor seals to negative impacts on the survival of salmon runs (Nelson 2020). Of the three most common pinniped species in inland Washington waters, harbor seals appear to have the largest predation effect on Chinook salmon in the Salish Sea (Chasco et al. 2017). Estimates of harbor seal consumption of Chinook salmon increased from 1.1 million fish in 1970 to 8.6 million in 2015 (Chasco et al. 2017). From 2004-2016, harbor seals predated up to 44% and 59% of the total estimated abundance of juvenile Chinook and juvenile Coho salmon produced in the Strait of Georgia, respectively (Nelson 2020). The magnitude of this direct predation impact is concerning for the recovery of salmon and the future of fishery dependent coastal communities in Washington State.

This scientific concern has been echoed in the policy sphere as well. Tribal, state, and federal managers have made it clear that the current abundance of pinnipeds in the Salish Sea is perceived as a threat to protected salmon stocks and a barrier to their recovery (Trites and Rosen 2019; Trzcinski 2020; Washington State Academy of Sciences 2022). The Washington state Governor’s Southern Resident Orca Task Force Report and Recommendations identified pinniped predation on Chinook salmon as a threat to SRKW and recommended research to determine the extent of the impact (Southern Resident Orca Task Force 2019). This concern was echoed in the Washington state legislature through the introduction of Senate Bill 5404, which describes pinniped predation as a threat to protected species and directs state, federal, and tribal managers to evaluate potential courses of action (WA Senate Bill 5404, 2021). The Washington State legislature requested that the Washington State Academy of Sciences review and summarize the current scientific knowledge about pinniped predation on salmonids. The resulting report supports that pinniped predation pressure on salmon is likely contributing to the lack of salmon recovery, and reiterates the need to act to address this issue despite remaining uncertainty (Washington State Academy of Sciences 2022).

While the potential impact of pinnipeds on salmon recovery is now widely acknowledged, there is little to no consensus on what actions should be taken, and by whom. Most managers agree that non-lethal deterrents are an ineffective way to reduce predation pressure (Scordino 2010). Some researchers are pushing for lethal removal (Nelson et al. 2020; McDonald 2023), but uncertainty about ecosystem-wide repercussions from large scale culls are still a major source of hesitation (Trzcinski 2020). Recent studies have echoed this doubt, cautioning that the ecosystem repercussions from large scale culls can be wide-reaching and can depend on a variety of region-specific factors, causing significant changes to trophic networks for uncertain salmon harvest and conservation benefit (Lessard et al. 2005; Morissette et al. 2012; Lennox et al. 2018; Blubaugh 2020). The desire to proceed with caution in the face of this considerable uncertainty means that managers are looking at lethal removal options that are more spatially and temporally explicit than a large-scale cull and are specifically developed to target improved salmon survival.

There are several lines of evidence, including archaeological records and traditional knowledge, that lead us to believe that tribal harvest could be an effective management structure for balancing these complicated objectives. Historically, humans were a main predator that regulated pinniped populations in the Pacific Northwest through hunting (Friedman and Gustafson 1975; Lyman 2003; Etnier 2007; Braje and Rick 2011). Pinniped hunts resulted in an ecosystem that was structured in a way that provided ample ecosystem services to the benefit of Puget Sound tribes (Etnier 2007; Braje and Rick 2011). Hunts would have controlled populations directly through removals (Lyman 1995, 2003; Hilderbrandt and Jones 2002), indirectly through disturbance (Becker et al. 2009; French et al. 2011), and spatially through the ecology of fear by excluding them from areas frequently used by humans, such as near settlements (Brown et al. 1999; Laundre et al. 2010; Rick et al. 2011; McHuron et al. 2018). This historic landscape of disturbance and harvest is a stark contrast to the distributions of pinnipeds today, where pinnipeds are often abundant near heavily populated areas and river mouths that were village sites (Wright et al. 2007; Scordino 2010; Götz and Janik 2013; Schakner et al. 2017a). The places where pinnipeds frequent, including river deltas, estuaries, and even miles upriver (Wright et al. 2007, 2010; Scordino 2010), are important salmon habitat and migratory corridors (Simenstad et al. 1982), and are places where pinnipeds would have been excluded or heavily deterred by human presence and hunting pressure.

Tribal harvest might be an effective management tool, but it is situated in a complex legal and political atmosphere. The right of “taking fish at usual and accustomed grounds” was reserved by tribes in the Puget Sound region through treaties signed in the 1850s and encompasses their right to harvest pinnipeds (*Makah Indian Tribe v. Quileute Indian Tribe*, 873 F.3d 1157 (9th Cir. 2017)). Puget Sound tribes currently do not publish regulations for directed pinniped hunting primarily due to legal concerns following the Anderson v. Evans court case on Makah whaling, which declared that the Makah Tribe must be granted a waiver of the MMPA take moratorium to exercise their right to hunt gray whales (Brand 2008). There is currently no clear judicial guidance on whether this ruling also applies to treaty-protected pinniped hunting rights. Resolving this ambiguity could prove legally risky for tribes. As a result, many tribes are treading carefully in seeking avenues to renew the exercise of this treaty right.

Despite these considerable complications, tribal harvest, either through an MMPA waiver or another pathway, is the lethal pinniped management option that appears most likely to reach implementation due to the actions of highly motivated tribal managers and the unique considerations that come with treaty-protected harvest rights. Resuming pinniped harvest could additionally strengthen tribal communities, cultures, and sovereignty, although it carries legal and political risks and places the burden of action on the Puget Sound tribes (Marker 2006).

Positionality Statement

It is important to situate myself and my worldview in relation to this work (Martin and and Mirraboopa 2003; Roberts et al. 2020; Hughes et al. 2023). I am a white, queer, cis-gendered female American citizen who grew up as a settler in Seattle, Washington on the traditional lands and waterways of the Duwamish, Muckleshoot, Tulalip, and Suquamish Tribes. Professionally, I am a marine mammal researcher and a current graduate student in fisheries science. I have spent much of my adult life working for the Makah Tribe in Neah Bay, WA and living, learning, and recreating on their traditional lands and waterways. I am dedicated to continuing to learn about Indigenous ways of knowing, Traditional Ecological Knowledge, and Indigenous Research Methodologies so I can participate in collaborative research that centers Indigenous peoples and communities with the goal that Indigenous perspectives and priorities will continue to take up more space in the realm of fisheries science and management (Ellis 2005; Silver et al. 2022). As non-native natural resource staff members working with tribal communities, it’s our responsibility to ensure access to critical resources for our communities in perpetuity. This work was conducted through that lens.

I am situated in a network of Indigenous governance, sovereignty, and leadership that directly and indirectly oversees this work (Latulippe and Klenk 2020). I am accountable to my supervisors, Tribal Council, and community at the Makah Tribe, where I live and work. I am accountable to my collaborators at Muckleshoot Indian Tribe and Nisqually Indian Tribe and their supervisors, tribal councils, and communities. I am accountable to 20 treaty tribes in Washington state through my collaboration with the Northwest Indian Fisheries Commission and because of the potential for this work to impact all of their treaty right exercise – I tread carefully and slowly with this knowledge. I am accountable to my PIs and committee members who have lent me their expertise, opinions, and support through this project. Lastly, I am accountable to the Academy and to the University of Washington School of Aquatic and Fishery Sciences through my opportunities as a graduate student and my responsibility to represent the school, college, university, and Academy well in all I do. This network of respect and accountability guides my decisions and ignites my passion to do this work well.

Description of Methodologies

Indigenist Research Process

Practicing an Indigenist research methodology as a White researcher and graduate student means centering Indigenous worldviews without claiming that I have access to that viewpoint myself (Hughes et al. 2023). As an early-career natural resource professional, this process is steeped in learning and humility for me, and I know I will continue to practice moving through my work with an Indigenist lens. Along this journey, I was lucky to learn informally from a few brilliant friends who shared their viewpoints with me and created space for me to learn from them. I especially want to thank Nicole Doran, Ryan Erhart, Cole Svec, and Kalena Kattil-deBrum for sharing their time, experiences, and ideas.

I believe that research is more than just science, it is about relationship building with collaborators and with the land itself (Wilson 2008; Fletcher et al. 2016; Wilson et al. 2020; Hughes et al. 2023). In the context of this project, this means being accountable to the communities I am working in by incorporating their priorities, honoring what they bring to the table, following agreements about data sharing, and communicating my results in accessible and useful ways (Beeman-Cadwallader et al. 2012). It also means being accountable to the land by spending time in the systems I am researching, seeing the bigger picture of this ecosystem and the other more-than-human lives that might be affected, and learning about the layers of legal, political, cultural, and ecological history that precede this work (Wilson 2008).

I was introduced to the Four Rs of Indigenous research by Professor Clarita Lefthand-Begay in 2023 and have allowed this framework to guide my decision-making at key moments of this project and to inform my reflections on implementing this process as a student (Kirkness and

Barnhardt 1991). I practiced *Respect* by elevating local and Indigenous knowledge about pinniped and salmon dynamics to equal standing with scientific literature and structuring my model around the understanding of these systems that was shared with me by project participants. I spent time in each of my case study systems, learning the place and seeing the layers of history and relationship between the land and communities. The participatory modeling process enabled participants to shape the project to ensure its *Relevance* to their management needs and its flexibility to adapt to the diversity of systems and dynamics in the region. I continue to have ongoing conversations with participants about useful model outputs and framing of results that will support decision-making internally and protect treaty rights from adversarial challenges. *Reciprocity* was more challenging to learn as someone who was trained as a scientist in Western educational institutions. Striving for reciprocal relationships during this project challenged me to show up to my collaborators as my whole self, to position myself with humility, to be vulnerable and offer my skills and enthusiasm, and to practice gratitude. By producing a tool that is useful to my collaborators, I hope their time and energy was worth it. By offering to get to know me as a person, I learned so much more about my collaborators and was able to share in their passion and learn from their deep knowledge. A multitude of cookies and donuts may have also helped.

The fourth R – *Responsibility* – was relatively intuitive to implement for this project. The topic of marine mammal management and harvest is sensitive in any context, but especially so when treaty rights are on the line. I relied heavily on my mentors (especially Jonathan Scordino and Eric Eberhard) to help me learn the history and context, navigate the critical legal nuances when communicating about this project, and ensure that my final products will help more than they will harm. I also was privy to potentially sensitive data about tribal marine mammal harvests and respecting that information was critical to the success of this project. My data management approach is outlined below.

Data Management

A key aspect of conducting research with sovereign nations is respecting and participating in preserving data sovereignty. For this project, we relied on data collected by tribes that describes the movement and abundance of animals in the ecosystems they steward. Respecting this information and fulfilling my responsibilities to uphold data sovereignty required that we plan for appropriate data management.

We used Github version control to manage model files in a repository shared among the PI team members (E Allyn, T Essington, A Berdahl, R Jones, J Scordino). We acknowledge that some data types associated with this project are sensitive to the entities sharing them, especially information that could impact treaty rights or that describes current marine mammal take. AI tools, including ChatGPT, were not used intentionally during any portion of this project to protect sensitive data and avoid contributing to adverse environmental impacts (Zhuk 2023). The PI team offered data sharing agreements to all collaborating agencies to facilitate information use in a fair and safe way, though no such agreements were requested or formalized. Mutual respect and open communication during this project were critical.

At the end of this project, all files associated with model development for the two case studies will be made available to our tribal collaborators on each respective case study. Any files containing sensitive information will be offered back to collaborators and then removed from the PI team's possession if requested (Menzies 2001). A version of the models will be made available in a public Github repository so that any interested parties, including other tribal nations, can use to support their own pinniped management agendas.

I acknowledge the dual-edged sword that is producing Western science tools to "support" or "validate" Indigenous management practices (Nadasdy 2005). This process was focused on bringing together knowledge from tribal natural resource experts from the Puget Sound region and creating a structure that can hold this shared knowledge, explore the way this knowledge fits together, and illustrate the dynamics of the system. The current legal and policy landscape in Washington State requires tribes to justify their marine mammal management practices under standards laid out in the Marine Mammal Protection Act and other fishery management legislation and regulations. Within this existing context and structure, tribal resource managers require tools to advocate for their treaty rights and their traditional practices. The tool we developed and tested in this thesis will hopefully support this effort. More broadly, the process of developing this tool facilitated information sharing between tribes on this topic and created a central repository for the shared understanding of the system that was developed through this process, which is now accessible to all participants.

Participatory Modeling Process

To carry out these principles and respect my network of accountability, we used a participatory modeling framework, which features engagement with collaborators and rights-holders in the problem formulation, design, implementation, and interpretation (Prell et al. 2007; Fulton et al. 2013; Essington et al. 2017; Schubotz 2020). For this project, the main participatory group included tribal natural resource staff involved in salmon and pinniped management, state and federal researchers and managers interested in salmon survival, and others with relevant experience in local ecosystems. The participatory modeling process for this project consisted of three primary phases described in detail below (Figure 1.1).

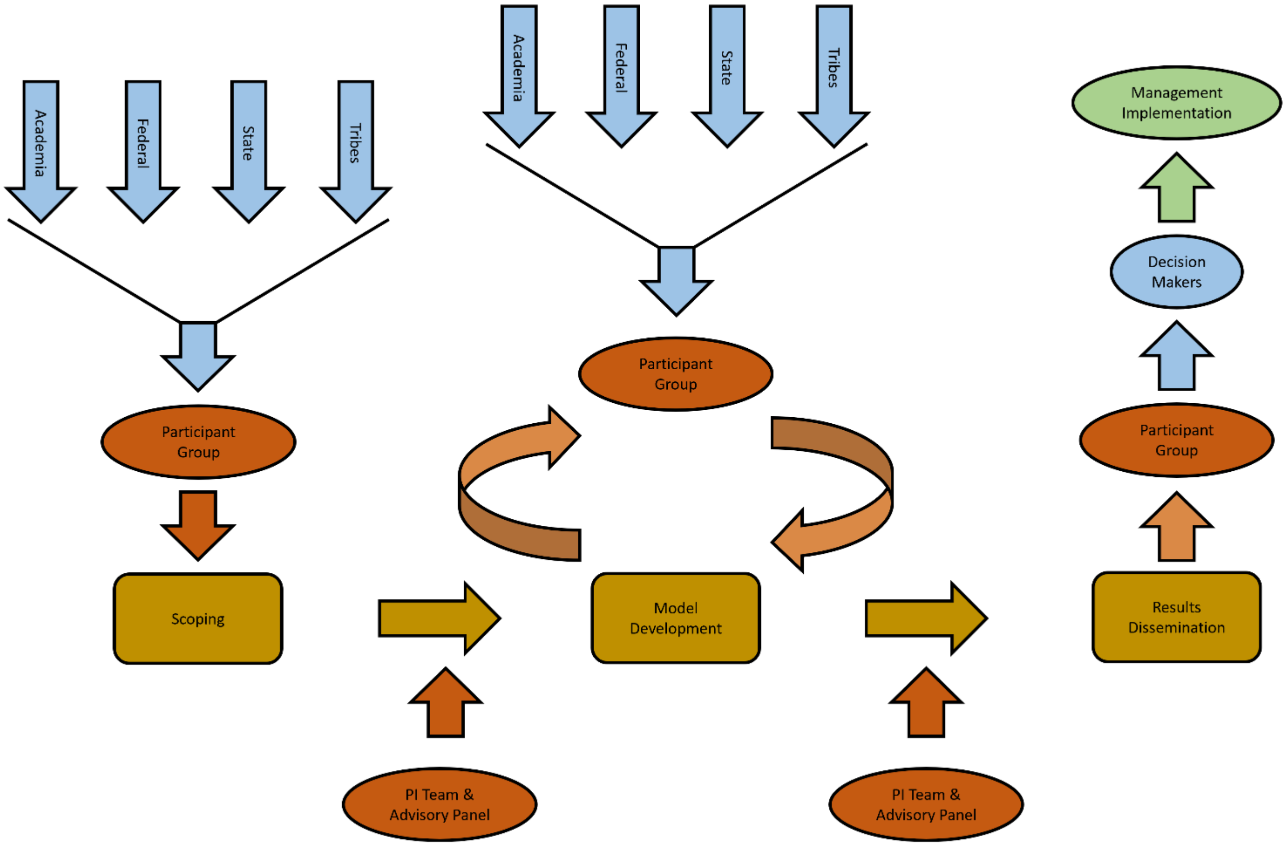

Figure 1.1: Diagram of the participatory modeling process as implemented for this project. The three major project phases are represented in gold. Management Implementation (green bubble) was outside the scope of this project, but an important goal of the project was to communicate the results clearly and usefully to decision-makers who could be able to implement the lessons learned in their management practices.

Phase One: Scoping

The first phase in the project was a series of information-gathering and goal-defining exercises. We met with representatives of 13 Washington treaty tribes in August 2022 to assess interest in this project and capacity to conduct future pinniped hunts. We then convened a diverse group of participants in a project scoping workshop in January 2023. Participants at this workshop included tribal, state, and federal salmon and marine mammal managers and researchers; researchers from academic institutions and non-profits; tribal fishers; and others with information relevant to the modeling process. The goal of this workshop was to collaboratively define the scope of the project and ensure that proposed project outputs aligned with the needs of participants. We also used this opportunity to gather information on site-specific vulnerability of salmon populations to pinniped predation in Puget Sound and the availability of useful data inputs. Summaries of each workshop are available in Appendix 2. In addition to these large participatory workshops, we also identified a smaller advisory panel of technical experts to weigh in on more immediate challenges encountered during the modeling process. This panel of experts included representatives from state and federal management agencies, tribal natural resource managers, tribal policy experts and individuals with modeling expertise.

Phase Two: Iterative Model Development

Using the information gathered at these workshops, a model was developed by the PI team where the structure, scenarios, and performance and risk measures were determined by the workshop participants. That is, all decisions about the model structure (e.g., spatial structure, population structure, temporal structure), parameterization (sources of information and uncertainty in parameter values), model breadth (which species are explicitly vs. implicitly modelled), were based on the key issues and uncertainties raised in the scoping workshop. This initial model structure was also heavily influenced by multiple site visits to both case study locations where I had the opportunity to learn from experts among the staff of the Muckleshoot and Nisqually tribes and build my own mental model of each system informed by their expertise and knowledge. This process was key to developing relationships, learning about the larger context at each site, and facilitating communication during the subsequent project steps.

Feedback was solicited and received from the full participant group, and relevant subgroups, at various stages of model development. In June 2024, we convened the advisory group to collect feedback on the model structure and inputs. This feedback was incorporated and the model structure along with preliminary results from both case studies were presented to the full participant group at a workshop in November 2024. Participants provided useful context about the utility of outputs, identified weaknesses in the model structure, and assisted with finding better parameter inputs. The PI team incorporated this feedback into further model improvements. Throughout this process, the PI team was in contact with collaborators with necessary expertise to advise on model development, provide relevant data inputs, and review preliminary findings.

Phase Three: Results Dissemination

The model structure and project process were presented to multiple audiences before completion to elicit feedback and ensure that all interested parties had an opportunity to participate. Presentations of in-progress work were given at the Idaho-Washington/British Columbia Joint Meeting of the American Fisheries Society in Spokane, WA in April 2024, at the Annual Meeting of the Northwest Student Chapter of the Society for Marine Mammalogy in May 2023 and May 2024, at the National American Fisheries Society Conference in Honolulu, HI in September 2024, and at the UW SAFS Graduate Student Symposium in November 2024.

Results from this project were presented to collaborators, workshop participants, and other interested parties during Phase Three of this work during May 2025. The group used this opportunity to discuss confidence in the model outputs, inspiration for future research projects, and implications of the results of this project for management and policy decisions in the realms of tribal marine mammal and fisheries management.

A full list of project participants and workshop attendees can be found in Appendix 2.

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Chapter 2 Agent-based modeling framework for exploring the impact of predator management scenarios on predator learning and foraging behavior

Introduction

The movement and behavior of animals across a landscape can be described using two complimentary axes of behavior that are frequently described using two ecological frameworks: Landscapes of Fear and Energy Landscapes. The Landscape of Fear describes the spatial variation in predation risk from the prey point of view (Laundré et al. 2001) and Energy Landscapes describes the spatial and temporal variation in energy savings available to an individual as they move and forage on a landscape. Through the Landscape of Fear lens, the landscape appears as a map of perceived safety and risk through which prey calculate the benefits of seeking the resources they need to survive against the risk of being eaten (Bleicher 2017; Gaynor et al. 2019; Wirsing et al. 2021). This information dictates the behavior of prey animals including minimizing time spent in high-risk areas, maintaining escape routes, and preferring landscapes with optimal cover or visibility to thwart detection by predators (Lima and Dill 1990; Brown and Kotler 2004; Wirsing et al. 2021). Integrated over multiple species and larger spatial and temporal scales, an Ecology of Fear governed by these behavioral patterns begins to emerge. The downstream effects of anti-predator behaviors that prey animals implement in response to their perceptions of fear can impact the physical landscape, outcomes of management actions, and the stable state of the ecosystem (Brown et al. 1999; Ripple et al. 2015). Managers can also use their understanding of ecology of fear principles to influence the behavior of wildlife in order to obtain conservation objectives, which is referred to as an applied ecology of fear (Smith et al. 2017; Gaynor et al. 2021; Ramirez et al. 2024). One example of an applied ecology of fear is the use of deterrents to reduce conflict between wildlife and livestock by inducing fear in predators. These tools are increasingly useful to managers when balancing the needs of multiple user groups with differing values alongside conservation mandates.

We can also understand the movement and behavior of wildlife through the variation in energy savings and opportunity on a landscape, more recently referred to as Energy Landscapes (Wilson et al. 2012; Shepard et al. 2013). This concept has been used to explain that animals conform to the ideal free distribution while choosing foraging locations (Wilson et al. 2012; Masello et al. 2017), how animals optimize their movement across complex terrain (Taylor et al. 1982; Nickel et al. 2021), and why the landscape of fear alone does not explain patterns in animal movement (Hammerschlag et al. 2015). The two axes of behavior represented by these frameworks – fear and energetics – are both critical when conceptualizing individual patch selection decisions that must balance predation risk and foraging success (Halsey 2016; Gallagher et al. 2017; Papastamatiou et al. 2024).

An important factor to consider when thinking about the impact of these broad ecological frameworks on individual patch selection decisions is the impact of individual behavioral specialization (McElreath and Strimling 2006; Bolnick et al. 2011). Relevant here are two dimensions of specialization: diet specialization and boldness (Sloan Wilson et al. 1994; Stamps 2007). Where prey availability is patchy, the energy landscape of individuals with differing diet preferences may cause them to make different decisions about movement and foraging tradeoffs that result in divergent space use patterns (Bolnick et al. 2003; Toscano et al. 2016). Individuals that have developed more aggressive or bold "personalities" may process fear or risk stimuli differently and exhibit less vigilant behaviors in the presence of predators or hunters (Lima and Dill 1990; Toscano et al. 2016). While these behavioral differences occur on an individual scale, they can have a significant impact on the wider ecosystem and our ability to predict the outcomes of management actions (Bolnick et al. 2003; Sanz-Aguilar et al. 2009).

In Puget Sound, WA, USA, managers are concerned about the magnitude of predatory interactions between pinnipeds (specifically harbor seals *Phoca* vitulina, California sea lions *Zalophus californianus*, and Steller sea lions *Eumetopias jubatus*) and Pacific salmon (*Oncorhynchus spp.*) and the potential impact on salmon conservation and recovery (Washington State Academy of Sciences 2022). To address this problem, tribal natural resource managers are interested in reviving pinniped management practices. Historically, tribal pinniped hunts managed pinniped populations both directly through removals and indirectly through applied landscape of fear principles. Evaluating the efficacy of potential tribal hunting regimes is complicated by the presence of “salmon specialist” individuals. Salmon specialists are pinnipeds that have been observed to spend more time foraging in areas where salmon migration is constricted (Yurk and Trites 2000; Wright et al. 2007, 2010), consume more salmon (Scordino 2010; Madson and Hevelingen 2017), and are more resilient to deterrence (Scordino 2010; Schakner et al. 2017a). There is uncertainty about how management efforts might be able to target these individuals and whether removals can be effective without identification of problem “specialist” animals and disruption of their social networks (Sanz-Aguilar et al. 2009; Bonneville Pinniped-Fishery Interaction Task Force 2017; Schakner et al. 2017b). Management actions that could target specialist individuals and either remove them from the system or interrupt their behavioral patterns would potentially require fewer pinniped mortalities and fewer management resources to achieve salmon survival objectives. At the moment, few systems have the ability to identify and track individual pinnipeds over the large spatial and time scales required to target them during management (Hatch et al. 2018; Freeman et al. 2022). Given the complex political and social ramifications of evoking tribal treaty rights to lethally remove charismatic megafauna, a better understanding of these aspects of management will be helpful for developing management strategies that are strongly supported within Western science frameworks (Courchamp et al. 2003; Treves and Karanth 2003; Morissette et al. 2012).

This project used a Participatory Modeling Process (PMP) to investigate how ecology of fear principles could be applied in pinniped-salmon systems to interrupt pinniped foraging behaviors and reduce the impacts of specialist foragers on salmon populations under tribal management. The PMP provides a framework for rights-holders, resource users, and local experts to shape the research objectives, model structure, data inputs, and utility of results. For this project, the process involved convening a group of experts from tribal, state, and federal management agencies at a series of workshops to solicit opinions about high-priority research objectives and collaboratively develop a modeling tool to address the objectives they identified. This paper describes a model that was developed to explore the behavioral responses of pinnipeds to the proposed management regimes and evaluate the potential benefits to the survival of returning adult salmon. The research objective of this modeling tool was to enable managers to compare pinniped management strategies and assess their impact on the survival of returning salmon. Using this model, we explore the efficacy of candidate management strategies and the sensitivity of management outcomes to key data gaps.

Methods

Model Rationale

We developed this model to simulate the dynamics between returning adult salmon and multiple species of pinniped predators within specific river systems or waterways where predation pressure is especially intense, which we refer to as gauntlets. We define the gauntlet using three criteria: 1) the prey species migrates through the gauntlet, producing a temporally pulsed prey field; 2) there is some barrier or challenge to the movement of the prey that causes them to be constrained; and 3) the predator has access to the prey while they navigate this constraint. Some examples of gauntlets in pinniped-salmon systems include a dam, fish ladder, narrowing of a natural river channel, or estuary where the physiological requirements of migrating across a thermal or salinity gradient constrain fish movement. The model simulates the predator-prey interactions occurring in the gauntlet, subject to foraging decisions and tradeoffs pinnipeds are making about the gauntlet.

The model described in this paper utilizes an agent-based model with an adapted Rescorla-Wagner classical conditioning component to simulate the learning, decision-making, and behavior of individual pinniped predators. The Rescorla-Wagner family of learning models use the mismatch between an individual's expected outcome of a trial and the actual outcome of a trial to adjust the individual's assessment of their surroundings and the risk-reward potential of their behaviors (Rescorla and Wagner 1972; Gershman et al. 2013; Paskewitz et al. 2022). We use this framework to represent how an individual's perception of danger (fear) or energy landscapes adapt based on their experiences, and how these perceptions affect foraging decisions. This framework allows the model to account for diversity of behavior within predator groups (i.e. diet and behavioral specialization) and to simulate individual learning based on their experiences with foraging success and hunting risk. The individual decision-making component of this model then informs each of the other dynamics that deal with social learning, salmon movement and mortality, and pinniped management (Figure 2.1).

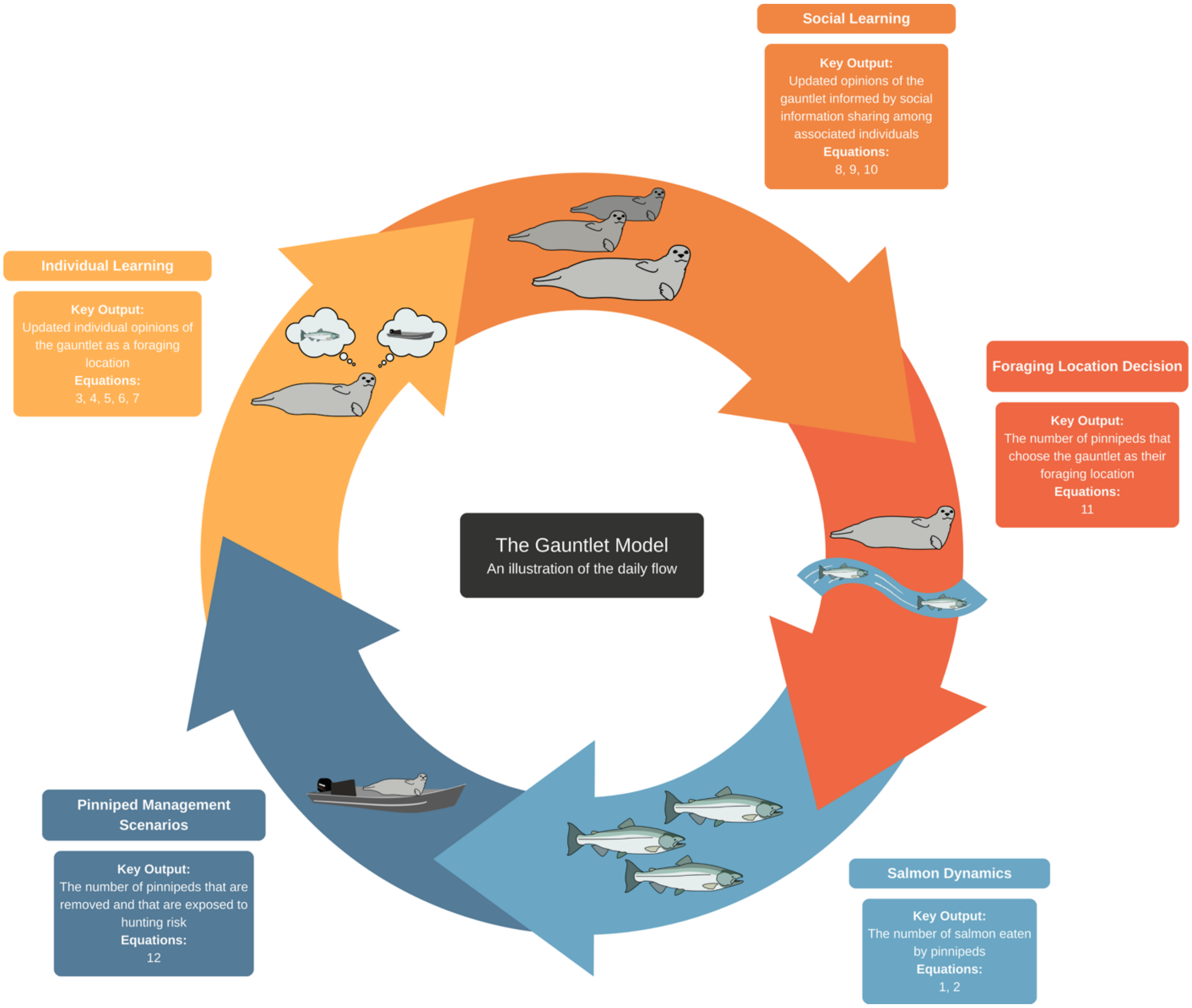

Figure 2.1: An illustration of the daily flow of one iteration of the gauntlet model dynamics as applied to pinniped-salmon gauntlet systems. Each step of the cycle happens once during a day where pinniped social learning and decision-making determine the number of predators in the gauntlet to predate on salmon and the number that are removed via management actions. The "key output" identifies the piece of information

that is calculated during that step and that informs the dynamics of the next step. Equations lists the model equations that describe the dynamics that occur during that step to produce the key output.

The model and associated outputs and visualizations were constructed in the R programming language (R Core Team 2023), with assistance from the following packages: anytime (Eddelbuettel 2020), dplyr (Wickham et al. 2023a), ggplot2 (Wickham 2016), lubridate (Grolemund and Wickham 2011), patchwork (Pedersen 2024), reshape2 (Wickham 2007), tidyr (Wickham et al. 2023b). The full model code is available in a GitHub repository (Allyn et al. 2025).

Model Description

Prey Dynamics

Equation 1 describes the daily number of salmon in the gauntlet at the start of an iteration (day; O_t)

$$O_t = f\left(O_{t-1}, N_{t-1,l=1}\right) + A_t \tag{1}$$

where $f(O_{t-1}N_{t-1,l=1})$ is the solution to the differential equation below (Equation 2) that calculates the survival and escapement of salmon in the gauntlet over the course of the previous day, and A_t is the number of salmon arriving at the gauntlet on day *t*.

The dynamics of salmon at the gauntlet over the course of a day are described by an ordinary differential equation whereby predation mortality is governed by a type II functional response and the number of pinnipeds foraging in the gauntlet $N_{t,l=1}$, the fishing (F_t) and other mortality (M) rate, and the rate at which salmon move through the gauntlet (E):

$$\frac{dO(T)}{dT} = \frac{\tau N_{t,l=1} \alpha O(T) N_{t,l=1}}{\tau + \alpha O(T) N_{t,l=1}} - F_t O(T) - MO(T) - EO(T) \tag{2}$$

where $O(T)$ is the number of salmon at the gauntlet at time T, τ is the daily maximum consumption rate, $N_{t,l=1}$ is the number of predators at the gauntlet, and α is the search and capture rate. The first term calculates the total salmon consumed using a flexible model that allows for prey and predator dependence in the functional response. M includes consumption by non-seal predators, disease, injury, environmental stress, and other sources of mortality not explicitly included in other terms. Escape rates (E) are the inverse of the average gauntlet residence time in days. The expression in Equation 2 was evaluated numerically using a fourth-order Runge Kutta algorithm to generate the $f(O_{t-1}, N_{t,l=1})$ term in Equation 1, and to calculate the per-capita foraging success of pinnipeds feeding at the gauntlet (the integration of the first term in Equation 2 over time T). The number of salmon that escape the gauntlet each day, as evaluated in Equation 2, is our main output of interest, expressed as a proportion of the total salmon run consumed.

Predator Individual Learning and Decision Making

The number of salmon consumed each day is dependent on the number of pinnipeds that are foraging at the gauntlet $N_{t,l=1}$, where subscript $l = 1$ refers to the gauntlet as a foraging location. The number of pinnipeds in the gauntlet is determined by an agent-based model that simulates individual decision-making and learning processes for every individual pinniped in the source population N_t. Each individual pinniped's decision to forage at the gauntlet is governed by a probability, i.e. the probability of foraging in the gauntlet each day. This probability is informed by the individual's knowledge about likely foraging success, X, and and hunting risk, Y, which both update daily for each predator (i), as described below (Equation 3).

X is a bounded variable (0 – 1), that tracks the individual pinniped's assessment about the fitness of the gauntlet as a foraging patch (Blumstein and Bouskila 1996; Mendelson et al. 2016). The change in X each day is based on the difference between the realized foraging gains of the prey patch they visited that day (either the gauntlet or not the gauntlet) and their current value of X which stores their recent foraging history (Bouskila and Blumstein 1992; Luttbeg and Trussell 2013). X updates as follows:

$$X_{t+1,i} = X_{ti} + \begin{cases} \sigma(1 - X_{ti}) & \text{if } (c_{ti} - w) > 0 \\ \sigma(0 - X_{ti}) & \text{if } (c_{ti} - w) \leq 0 \end{cases} \tag{3}$$

where σ represents the learning rate, c_{ti} is the energetic foraging gain of salmon prey at day 't', and w is the foraging gain of salmon prey they might have been expected to obtain outside the gauntlet (Table 2.1). When c_{ti} is greater than w, X increases toward 1. When the individual does not successfully capture more salmon than the baseline value w, X declines toward 0. When individuals forage at the gauntlet, the change in X is mediated by σ which represents the learning rate. When individuals do not forage at the gauntlet, they become uncertain about the fitness of the gauntlet as a foraging patch. X declines toward a baseline value (X_{base}) at rate d which represents the speed at which extinction of memory occurs (Yamaguchi 2000; Quirk 2002):

$$X_{t+1,i} = X_{ti} + d(X_{base} - X_{ti}). \tag{4}$$

Table 2.1 Parameter inputs for predator learning, consumption, and fear conditioning in the gauntlet model. The Manipulation Range column shows the range of values over which the parameter sensitivity was explored. Full parameter and variable tables can be found in Chapter 2 Appendix 1, 2, and 3. Parameters whose descriptions lack explicit units are unitless.

Parameter	**Description**	**Non-specialist value (Specialist value)**	**Manipulation Range**
X_{base}	Baseline X value	0.01 (0.1)	0 – 0.25 (0 – 0.5)
Y_{base}	Baseline Y value	0	NA
z	width of the Receptivity curve	15	3 - 30
θ	Height of the Receptivity curve	√0.5	0 - 1
σ	Foraging learning rate	0.15 (0.3)	0.01 – 0.3 (0.02 – 0.6)
d	Foraging memory decay rate	0.1	0 – 0.3
L	Fear cue association learning rate	0.15	0.01 – 0.3
ρ	Fear cue association decay rate	0.05	0 – 0.3

$\boldsymbol{\tau}$	Maximum consumption rate (prey day $^{-1}$)	6	1 - 10
$\boldsymbol{\alpha}$	Search and capture rate (pinniped $^{-1}$day $^{-1}$)	0.6	0.2 – 0.8
$\boldsymbol{w}$	Minimum foraging success kJ (kcal)	1,485.32 (355)	418.4 – 14,853.2 (100 – 3550)

Y is a variable which keeps track of an individual's fear conditioning in response to exposure to hunting activity and associated cues. This part of the model uses an adaptation of the Rescorla-Wagner learning model that incorporates association decay as a mechanism for forgetting or weakening of associations during non-exposure (Rescorla and Wagner 1972; Yamaguchi 2000; Paskewitz et al. 2022). The model keeps track of how individuals predict the occurrence of an outcome (y) using associated cues (r_k, where subscript k is an index that identifies each cue). Here, the outcome is exposure to hunting activity and the related risk of being injured or killed. In this model we keep track of three cues: the presence of fishing activity, the presence of hunting activity, and a third cue that represents the remaining physical and geographic cues associated with the gauntlet as a foraging location. When a cue is presented to individual seal i on day t, $r_k = 1$. Otherwise, $r_k = 0$. The cue associated with fishing activity, $r_{k=1}$, is present when fishing boats are present in the gauntlet. The cue associated with hunting activity, $r_{k=2}$, is present when pinniped hunting is occurring. The cue associated with the gauntlet context, $r_{k=3}$, is present whenever the seal forages at the gauntlet. Each time step, seals are presented with a set of cues (r_k) and either experience safe foraging conditions $(y = 1)$ or observe hunting activity $(y = 0)$. Their ability to predict the safety of the gauntlet relies on updating the association weights (β) between these cues and the risk of being hunted according to their experience, as follows:

$$\beta_{t+1ik} = \beta_{tik} + Lr_{tk}(y_t - \hat{y}_{ti}) - \rho\beta_{tik} \tag{5}$$

where β is the association weight between cue k and hunting risk for individual pinniped i on day t, L is the learning rate, r_k = 1 when cue k is present, and ρ is the rate of association decay (i.e. forgetting). Equation 5 can be thought of as updating β for cue k by adding the product of the learning rate for cue k and the prediction error for y, then subtracting the memory that was lost (Paskewitz et al. 2022). These weights are used to calculate the individual seal's prediction of the risk of foraging at the gauntlet, $\hat{y}$, which is always a value between 0 and 1:

$$\hat{y}_{ti} = \sum^{k} \beta_{t-1ik} \,. \tag{6}$$

In this context, $\hat{y}$ represents the predicted risk of the gauntlet, where values close to 1 indicate high risk. We transform $\hat{y}$ into a probability of choosing the gauntlet as a safe place to forage, Y, by subtracting $\hat{y}$ from 1.

These two learning terms, X and Y, are then combined into a single probability of foraging at the gauntlet, P, using a multiplicative method to ensure that a probability of 0 resulting from either mode of learning would preclude selection of the gauntlet as a foraging location:

$$P_{ti} = X_{ti} Y_{ti}. \tag{7}$$

Predator Social Learning

The model also incorporates social learning where individuals share information based on the social structure of the pinniped group. Previous work on the Columbia River, WA, USA showed that the spread of foraging behavior targeting the Bonneville Dam (which could be classified as a gauntlet according to our criteria) was highly influential in determining the number of pinnipeds exhibiting that behavior, and on the impact to migrating salmon (Schakner et al. 2016). The social structure of the pinniped group in that study was represented by a matrix of associations that was developed using resight data, where individually-identified California sea lions that hauled out together more frequently were given a higher social association value (Schakner et al. 2017b). We mimic this social association matrix for the predator group modeled here and allow each individual's learning process to be influenced by their associations.

Before individual seals select their foraging destination, they undergo a round of social information sharing. Each individual's connection to the others in the source pool is represented by the social association matrix described above where the value in each cell is either 1 (associated) or 0 (not associated). We assume that individuals with strong opinions about foraging at the gauntlet that arise from their own experiences will be less receptive to social information than naïve individuals. We calculate a receptivity based on each learning variable, X and Y, using the same equation (Equation 8) with different parameterizations, shown here for X:

$$R(X_{ti}) = \frac{\theta\left(X_{ti}^{\frac{u(z-2)+1}{1-u}-1}(1-X_{ti})^{z-1}\right)}{u^{\frac{u(z-2)+1}{1-u}-1}(1-u)^{z-1}} \tag{8}$$

where θ is the maximum receptivity, the value of X or Y where receptivity peaks is represented by u, and z is related to the width of the function (Figure 2.2). For X, we assume that receptivity peaks at X_{base}, or the baseline expectation of foraging success at the gauntlet for a naïve individual. For Y, we expect receptivity to peak at the naïve value of 0, where naïve individuals do not have any experiences that would cause them to expect hunting risk. Parameters θ and z are the same when calculating receptivity for X and Y.

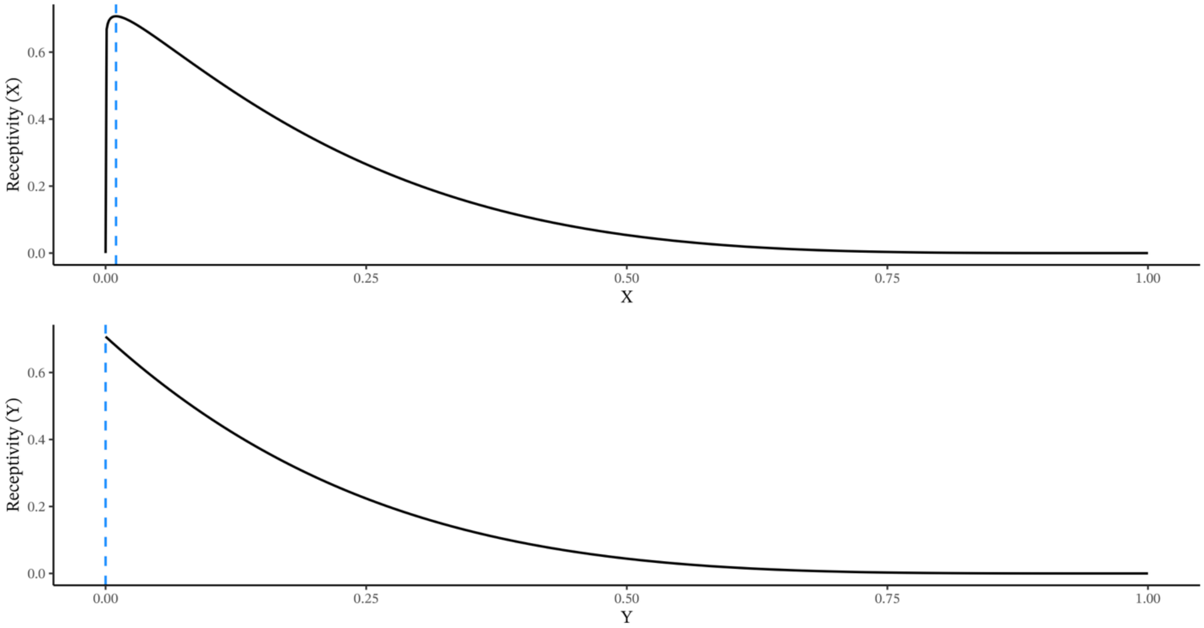

Figure 2.2: The shape of the relationship between X *and* Y *and their respective receptivity terms*

We calculate a final receptivity R using a multiplicative method so that the individual's experiences with both aspects of learning have a bearing on receptivity.

$$R_{ti} = R(X_{ti})R(Y_{ti}) \tag{9}$$

Any individuals with non-zero associations are included in the individual's social circle and their probabilities (P_{ti}) are averaged to create the social information, η, that the individual will incorporate into their decision-making process. Information is assimilated using a second probability, P_S, which describes the individual's probability of choosing to go to the gauntlet given both their individual experiences and the social information they have learned:

$$P_{S_{ti}} = (1 - R_{ti})P_{ti} + R_{ti}\eta_{ti} \tag{10}$$

where P_{ti} comes from Equation 7 and P_S is the probability that is used to make the foraging decision for individual *i* on day t. This decision is made as follows:

$$\phi_{ti} \sim Bernoulli\left(P_{S_{ti}}\right) \tag{11}$$

where success $(\phi = 1)$ results in the individual foraging at the gauntlet.

Predator Management Scenarios

Using this model, we explored the impacts of the predator learning dynamics described above on the efficacy of three predator management strategies: no removals ("Base"), lethal removals that cause fear ("Fear"; i.e. hunting or culling), and lethal removals that do not cause fear ("No Fear"; i.e. trapping and euthanasia). The no action Base scenario is included as a baseline comparison for the action strategies, and to help illustrate the consequences of no action. Removal of predators was calculated using the same harvest function for each strategy,

$$H_t = ghB_tN_{tl=1} \tag{12}$$

where g is the amount of spatial overlap between hunting effort and predators foraging in the gauntlet, h is the efficiency of hunters targeting predators they encounter, B is a measure of hunting effort, and N is the number of predators foraging in the gauntlet (Arreguín-Sánchez 1996). The spatial overlap between hunters and predators (g) was also used to determine the number of predators that were directly exposed to hunting activity to develop fear. The proportion of predators that were exposed to hunting activity was calculated and a sample of the predators at the gauntlet that day was taken to identify the individuals that would develop fear. When we simulated management scenarios with fear, predators that were exposed to hunting activity were allowed to develop fear where $y_t = 1$ in Equation 5. When we simulated scenarios where predators did not develop fear, we set $y_t = 0$ for all predators.

Analysis

Simulated Predator and Prey Populations

We used simulated prey and predator populations to test and illustrate the dynamics of the model, based loosely on the behavior and bioenergetics of harbor seals (*Phoca vitulina*) as the predator and Sockeye salmon (*Oncorhynchus nerka*) as the prey. A Gaussian salmon arrival curve with a total abundance of 10,000 and standard deviation of 8 days was used to calculate A_t (Figure 2.3). The prey population was assumed to have a two-day residence time (i.e., E = 0.5) in the gauntlet and a total average energy content of 20,920 kJ (5,000 kcal) per salmon. The baseline natural mortality rate of the prey population was simulated as 0.0005 day^{-1}. In all scenarios we set all fishing terms to zero to indicate the absence of fishing effort in these manipulations.

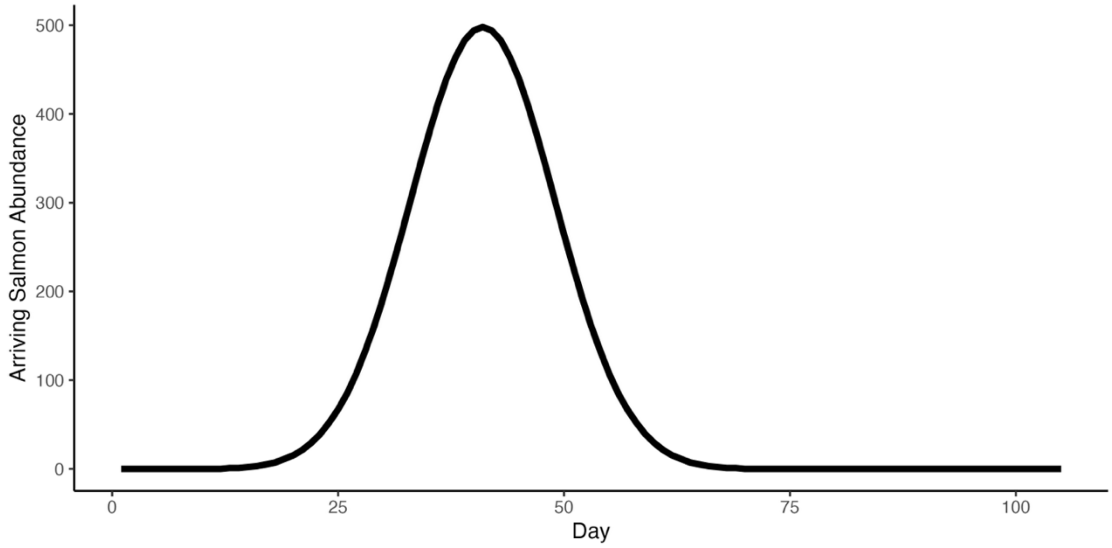

Figure 2.3: Daily number of salmon arriving to the gauntlet

We modeled a single predator population with an abundance of 100 seals. Naïve individuals were assumed to make up 70% of the population, with the remaining 30% exhibiting specialist gauntlet foraging behaviors and parameterized as described in Table 2.1. Each predator had a daily energetic requirement of 14,853.2 kJ (3,550 kcal; based off requirements for harbor seals as described in (Howard et al. 2013; Chasco et al. 2017)).

Management Scenarios

Gauntlets can exist in a variety of socio-political settings that dictate the types and magnitudes of management actions that might be legal or feasible. The common goal of these management approaches is to reduce encounters between pinnipeds and salmon to improve salmon survival. Here we explore a key characteristic of possible management scenarios: the impact of implementing management scenarios that cause fear conditioning in predators. In the Columbia River, problem individuals are trapped and euthanized offsite, so the other pinnipeds present in the area are not exposed to activity that might cause them to fear the place where takes occur (Tidwell et al. 2021). In contrast, boat-based hunting carried out via firearm is more visible and behaviorally disruptive, causing individuals in proximity to that activity to perceive the risk to their own safety and to fear the area. To illustrate this dynamic, we ran three management scenario parameterizations: Base, Fear, and No Fear. In the Base scenario, no seal hunting occurred. In both the Fear and No Fear scenarios, seal hunting occurred on every day that salmon were present in the gauntlet, but seals were only able to develop fear in the Fear scenario. We assumed a 50% spatial overlap between hunting activity and foraging predators (g), and a 10% hunting efficiency of encountered predators (h). For each scenario, the model was run 100 times with the same parameters and relevant variables were saved from each iteration.

Level of Management Effort Necessary to Achieve Objectives

All management manipulations were compared to the base run scenario where no seal hunting occurred. To explore the amount of hunting effort required to produce improved salmon survival through the gauntlet, we simulated hunting schedules to test a few different aspects of hunting frequency and timing. The first manipulations tested the effects of various levels of effort within a weekly schedule (i.e. 1 - 7 days per week). The second manipulations tested the effects of lapses in effort on seal behavior (i.e. one day of effort followed by a break of 1 – 21 days). We assumed a 50% spatial overlap between hunting activity and foraging predators (g), and a 10% hunting efficiency of encountered predators (h). For each scenario, the model was run 100 times with the same parameters and relevant variables were saved from each iteration.

Identifying Data Gaps and Exploring Model Sensitivity

We conducted an individual parameter perturbation to probe the model for key uncertainties and sensitivities in parameter values. Single parameter manipulations were run using the Fear scenario where predator removals occurred and caused fear conditioning. For each exploration, 100 Monte Carlo simulations were run using a random draw from the ranges described in Table 2.1 and relevant variables were saved to evaluate outputs.

Results

The Base run where no pinniped management was implemented resulted in the highest consumption of salmon and the lowest salmon escapement (Table 2.2). In the Base run, seal attendance at the gauntlet increased with salmon presence at the gauntlet, and then abruptly declined when the abundance of salmon declined below the minimum abundance needed to result in higher foraging success on salmon in the gauntlet than outside the gauntlet (Figure 2.4). The Fear scenario resulted in the lowest proportion of salmon consumed and highest proportion escaped. The No Fear scenario did not result in a notable improvement in consumption from the Base scenario, though seal attendance at the gauntlet was decreased.

Table 2.2: Pinniped management scenario outputs showing average salmon consumed, average % of run consumed, and average number of seals removed under a Base model run, No Fear scenario, and Fear scenario. Values in parentheses describe the inner 90% quantile.

Scenario	**Salmon Consumed**	**% of Run Consumed**	**Seals Removed**
Base	3,448 (3,086 – 3,691)	34.5%	0
No Fear	3,192 (2,798 – 3,455)	31.9%	34.7 (28.0 – 39.0)
Fear	2,305 (1,908 – 2,571)	23.1%	7.4 (0 – 14.1)

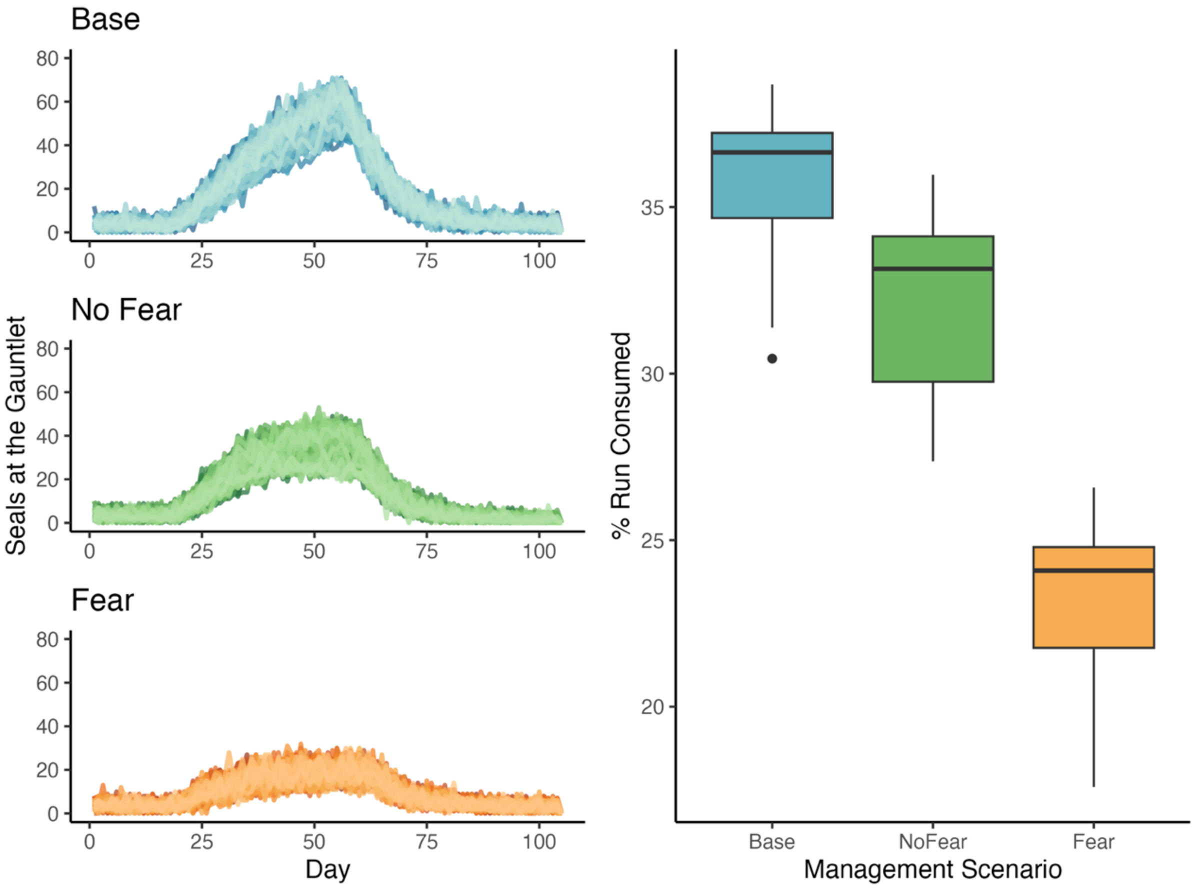

Figure 2.4: Left panels show seal presence at the gauntlet under three management scenarios: Base run with no management (top); No Fear where pinniped management was implemented using methods that prevent fear conditioning (middle); and Fear where removals caused fear (bottom). Each line depicts a unique model run. Right panel shows the total proportion of salmon consumed by seals during each scenario (Base, No Fear, Fear from left to right).

Longer lapses in hunting effort and fewer days of effort per week both reduce the efficacy of pinniped management (Figure 2.5). Lapses in hunting effort of even one day resulted in higher salmon consumption, but the effect of longer lapses plateaued after ca. 5 – 6 days. Similarly, more days of effort per week decreased the proportion of consumed salmon and the number of seals using the gauntlet daily, such that the management scenarios with fewer than 5 days per week were less effective than those that more frequent hunting effort.

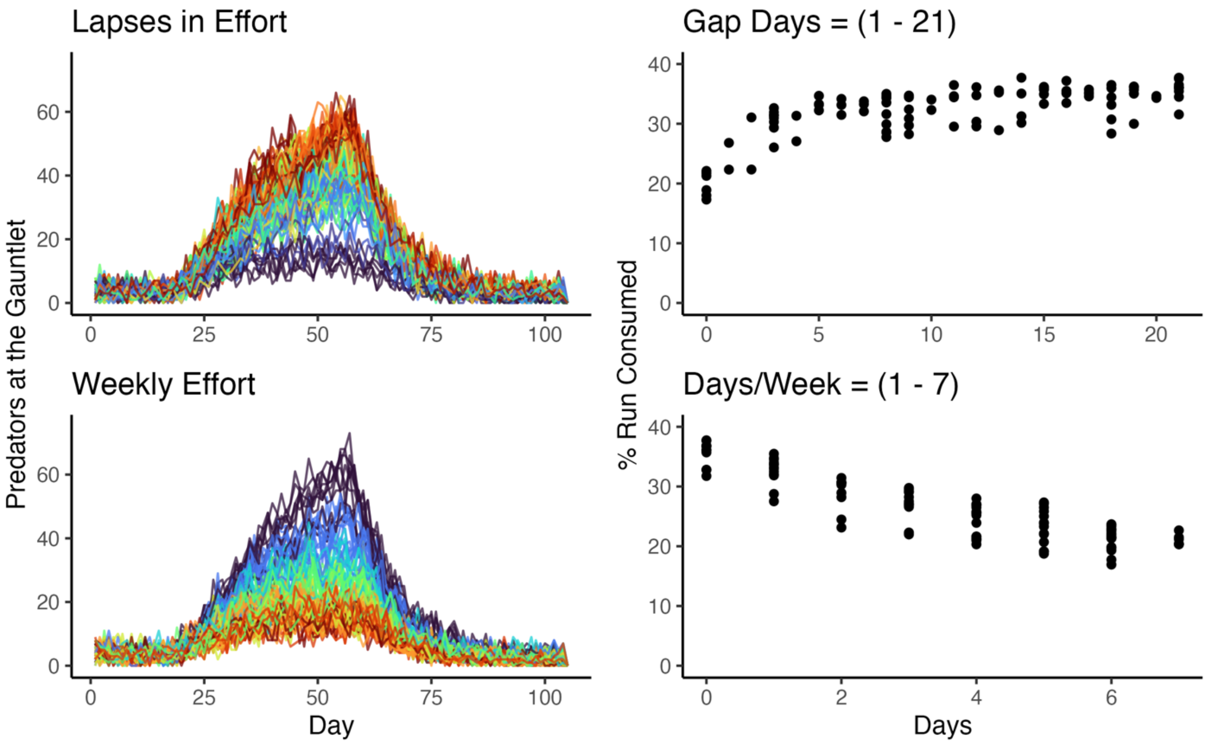

Figure 2.5: The effects of hunting effort timing on seal presence in the gauntlet and the proportion of salmon consumed. Left panels show simulated abundance of predators foraging at the gauntlet each day, where warmer colors indicate larger values (longer lapses and more days of effort per week), and cooler colors indicate smaller values (shorter lapses and fewer days of effort per week). Right panels show the percent of run consumed for each model simulation. Top row depicts management scenarios where there are different number of days between hunting efforts. Bottom row depicts management scenarios in terms of the number of days per week that hunting occurred.

The modeled percent of run consumed was highly sensitive to several model parameters (Figure 2.6). The proportion of individuals exhibiting specialist behaviors, the effective search and capture rate of the predator (α), maximum consumption rate (τ), and foraging learning rate (σ) (Figure 2.6) all had relatively large effects on salmon consumption. The sensitivity of the model to some of these terms was curvilinear (baseline X value, foraging learning rate σ), while was nearly linear for the other parameters. The model was not sensitive to parameters that affect social receptivity *(θ and z)*, the learning decay rates *(d and ρ)*, or the baseline foraging success *(w)*.

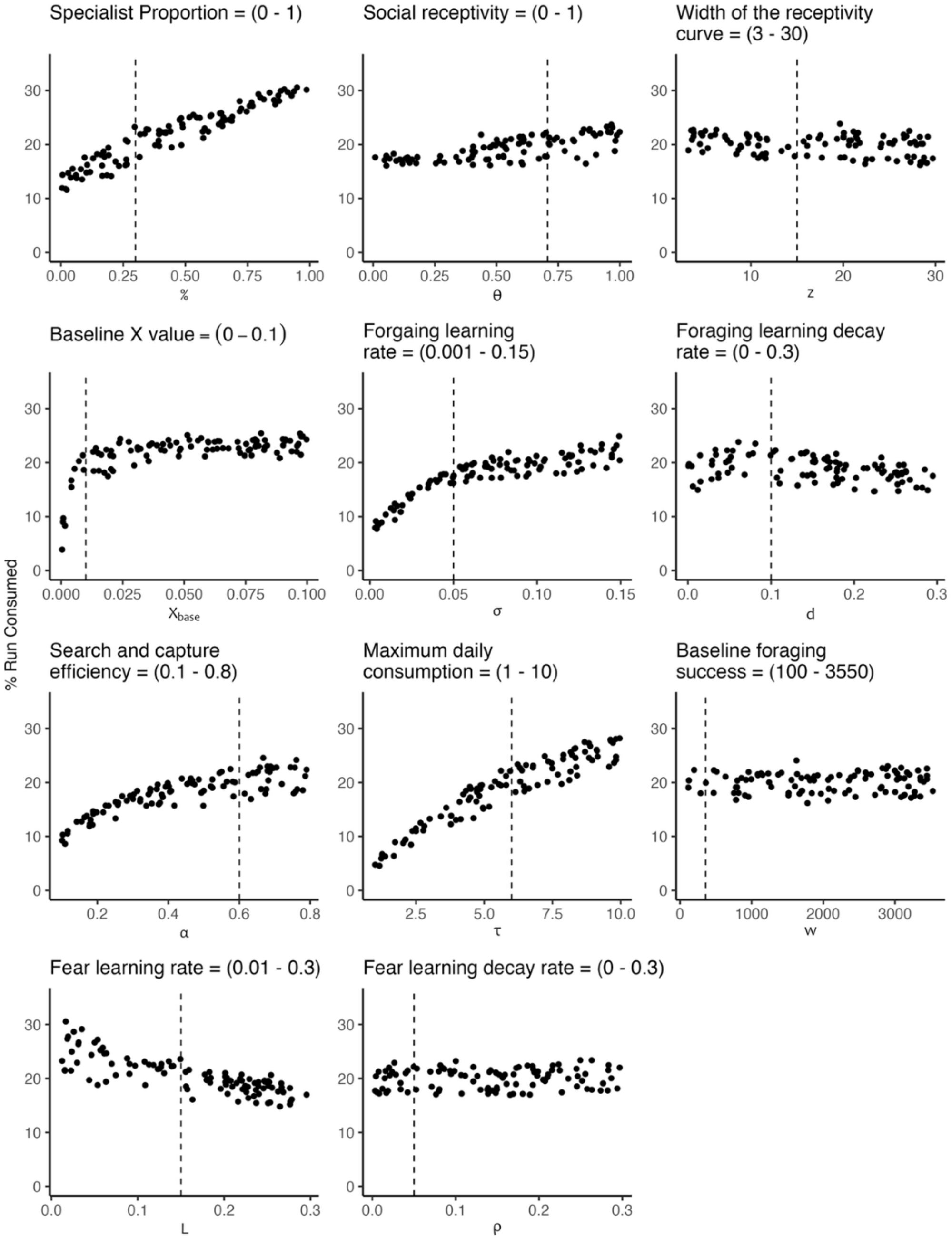

Figure 2.6: Each panel shows the sensitivity of a single parameter with regard to total salmon consumption. The vertical dashed lines indicate the nominal parameter value use in Base scenario runs. The range of values in the title of each plot indicates the manipulation range over which the sensitivity was explored.

The sensitivity of the model to the fear conditioning learning rate, parameter L, depended on the harvest scenario (Figure 2.7). When harvest scenarios specified lower hunting efficiency (q = 0.1), the simulated salmon consumption rate declined with increasing learning rate. However, when hunting efficiency was set to higher values (q = 0.3; q = 0.5), the simulated salmon consumption by pinnipeds was insensitive to the fear learning rate, suggesting that under these scenarios, the direct effect of hunting on seal survival was more important than its indirect effects through fear conditioning.

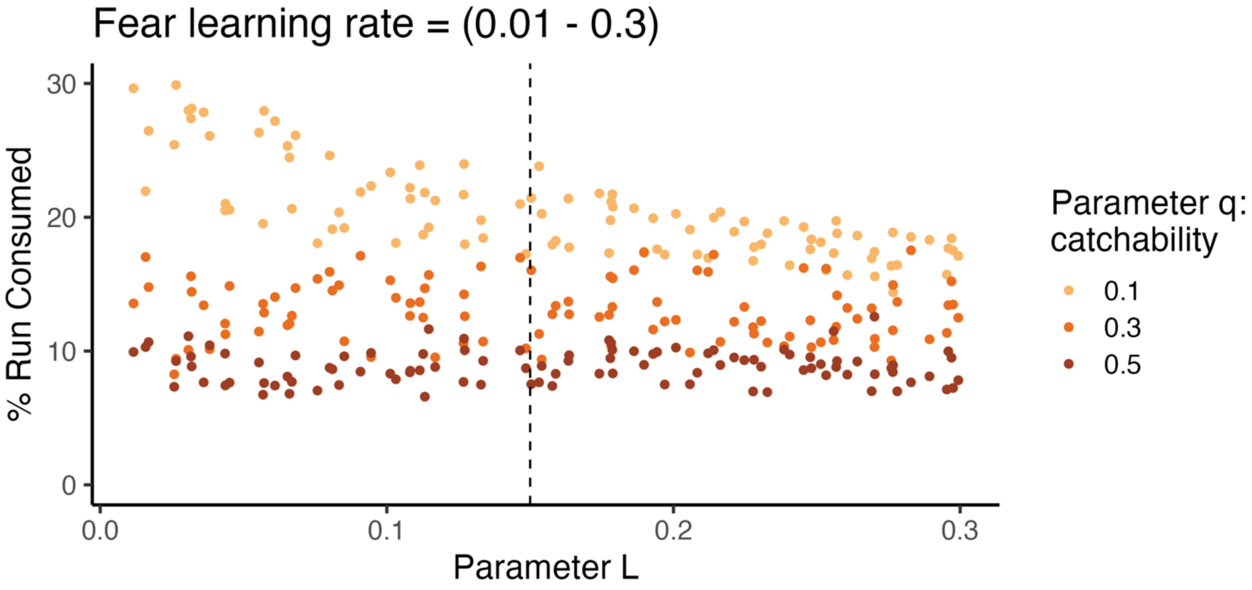

Figure 2.7: Sensitivity of salmon consumption to the fear learning rate (parameter L*) under varying levels of harvest intensity. Harvest intensity was manipulated by varying the catchability parameter* q *at three levels (0.1, 0.3, 0.5).*

While we saw a mild impact of social learning (parameter θ) on seal presence in the gauntlet in the single parameter manipulations carried out using the Fear scenario, those behavioral changes did not translate into notable differences in salmon consumption over the parameter manipulation ranges for any of the management scenarios (Figure 2.8). The degree of sensitivity of salmon consumption to social receptivity under all three harvest scenarios was similar.

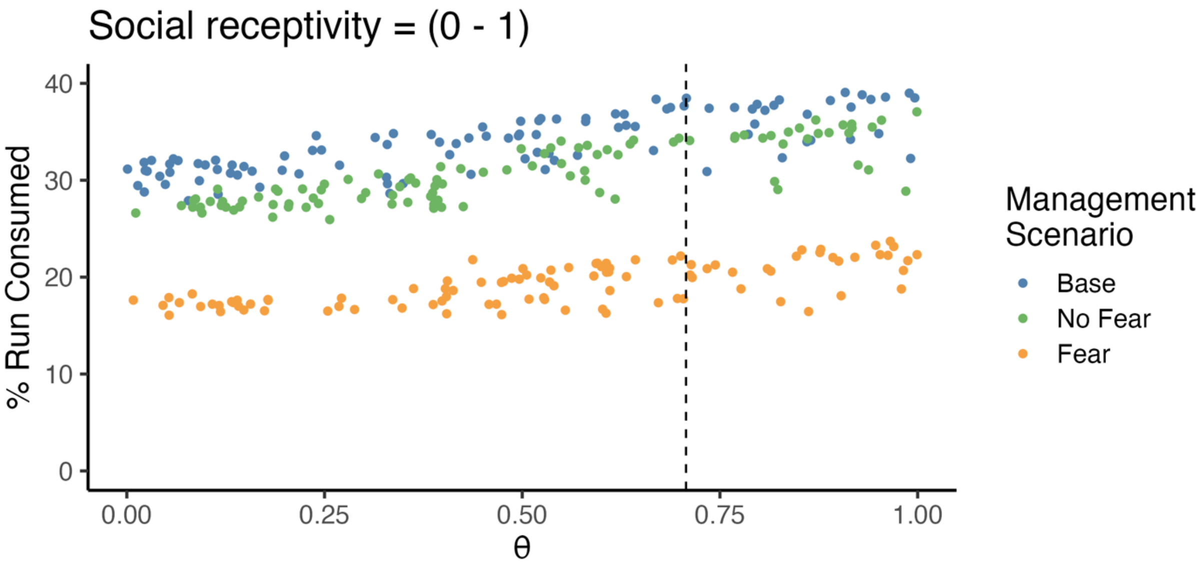

Figure 2.8: Sensitivity of salmon consumption to social information sharing (parameter θ) under all three management scenarios (Base, No Fear, Fear).

Discussion

Here we applied the Rescorla-Wagner classical conditioning in a novel context of pinniped management for salmon conservation and fisheries. We find that fear conditioning can be an important part of a management strategy that aims to use predator hunting to improve salmon escapement through gauntlets. Specifically, management scenarios that included a fear conditioning component resulted in notably improved salmon survival (Figure 2.4). Moreover, these scenarios achieved benefits to salmon survival with far fewer pinniped removals than scenarios that did not include fear conditioning (Table 2.2). In a system where managers are challenged with threatened prey populations and charismatic predators, the ability to effectively manage pinniped populations while minimizing pinniped removals is a powerful tool. This model allows managers to explore those dynamics and make informed decisions for their systems.

The possibility of achieving improvements in salmon survival with minimal pinniped removals should be appealing to many, though current conservation legislature may be acting as a roadblock. The Marine Mammal Protection Act (MMPA) of 1972 and the Amendments of 1994 provide a pathway for pinniped removal under Section 120 authorization. Under the current implementation of this authorization at the Columbia River, individually identified nuisance animals are trapped in the gauntlet and euthanized offsite, which prevents the other pinnipeds in the area from developing a fear association with that activity, similar to the modeled No Fear scenario. While this practice was developed as a humane way to end animal lives as required by the Act, we show here that it may be requiring that more pinnipeds be lethally removed than would be necessary if managers implemented removals using fear conditioning principles as in the Fear scenario. Much of the MMPA was founded on the principles of protecting marine mammal populations and reducing take, but in this case the way managers are implementing their authority under the Act may have the opposite effect.

Tribal natural resource managers may be uniquely positioned to implement applied ecology of fear principles to protect salmon resources. The Fear scenario was developed in part to explore what we believe the impacts of Indigenous management in the region would have been on the distribution and abundance of pinnipeds and the resulting benefits for salmon (Rick et al. 2011). In the Fear scenario, seals were deterred from the gauntlet, protecting returning adult salmon as they navigated one of their most crucial life stages. There are a growing number of examples of Indigenous management practices that seemed – to Western scientific eyes – to be centered around harvest of a resource, but actually have wide-reaching impacts on the structure of the ecosystem and the availability of other critical community resources, like “streamscaping”, clam garden cultivation, and herring transplantation (Lepofsky and Caldwell 2013; Thornton and Deur 2015; Comberti et al. 2015). While pinniped harvest continues to primarily be an important cultural practice for Pacific Northwest native communities, our work supports the idea that pinniped hunting likely served a secondary function of manipulating the movement and behavior of known salmon predators to protect valuable salmon resources and ensure access to salmon into the future.

Managing according to applied ecology of fear principles may be useful in gauntlet systems, but it also requires frequent maintenance of pinniped fear associations via repeat exposure. We explored the impact of various management schedules and found that re-exposure would likely need to occur regularly, and likely for multiple days per week to be as effective as we describe. The effectiveness of management at reducing pinniped presence in the gauntlet declines as the number of days between management effort increases and as the number of days per week that management is enacted decreases (Figure 2.5). Currently this type of consistent management effort is limited by the policies that govern one of the few clear pathways for pinniped removals to occur via fear-inducing methods: the right for tribal fishers to protect their gear and catch from pinniped predators using both non-lethal and lethal methods. While these activities result in fear-conditioning and reduced pinniped presence in the gauntlet during the fishing season, declining salmon populations have resulted in shorter and less frequent fishing seasons, or complete fishery closures. When fisheries are closed, pinnipeds have free access to the gauntlet. This study shows that greater salmon survival through the gauntlet could be achieved by continuing pinniped management actions even when fisheries are closed to protect migrating fish. Managers need the flexibility to determine the level of management effort that balances their escapement goals with their available resources.

While we saw a moderate impact of social learning (parameter θ) on seal presence in the gauntlet in the single parameter manipulations carried out using the Fear scenario, those behavioral changes did not translate into notable differences in salmon consumption over the parameter manipulation ranges for any of the management scenarios. The similar degree of sensitivity of salmon consumption to social receptivity under all three harvest scenarios indicates that social learning about fear was not an influential aspect of this model, while social learning about foraging opportunities was mildly influential. The model described in this paper makes use of a simple method of social information sharing. Other models of social information transfer and collective learning have explored the intricacies of this space and offer more creative ways of representing behavioral patterns in wild populations (Kao et al. 2014; Falcón-Cortés et al. 2019; Gildea et al. 2025). However, studies on the social behavior of pinnipeds in the wild are extremely limited, and the approach we used here makes use of the data available

(Schakner et al. 2017b). Ongoing work to individually identify harbor seals without branding and track their movements have led to insights about site fidelity and differences in individual foraging success (Birenbaum et al. 2022; Freeman et al. 2022; Edison et al. 2024), but have yet to be applied to more complex social behavior inquiries. Understanding the social associations present in wild populations can be useful in monitoring population health and connectivity, and designing appropriate management interventions when necessary (Snijders et al. 2017). In populations where social information transmission about fear is observed to be an important behavioral dynamic, a more complex method of modeling social learning may be warranted.

As with any modeling exercise, we made several assumptions about gauntlet systems to explore the key dynamics of the system. We do not incorporate an explicit spatial component to explore movement and distribution within the gauntlet. The gauntlet is intended to represent an explicitly defined and relatively small spatial area where the impacts of pinnipeds on salmon are heightened. Heterogeneity in the interactions between pinnipeds and salmon within the gauntlet would need to be addressed through another mechanism, perhaps by linking together multiple gauntlets that could each capture the dynamics in a sub-area of the gauntlet. In our initial explorations of the gauntlet model presented here we did not find this granularity necessary. We also assumed that all individuals within each population – pinniped or salmon – were identical on many characteristics including bioenergetics and diet. Specialist pinnipeds in the model were more likely to choose to forage in the gauntlet but were assumed to have the same foraging success on salmon as the non-specialist pinnipeds. While pinniped foraging success can be highly variable within populations (Harcourt 1993; Weise and Harvey 2008; Wilson et al. 2014; Hoskins et al. 2015; McHuron et al. 2016), studies show that individuals that frequent gauntlet areas do not necessarily show greater foraging success on salmon (Schakner et al. 2017b; Freeman et al. 2022). We therefore modeled the foraging success of all pinnipeds in the gauntlet identically to represent average foraging success. We could have underestimated the efficacy of management on reducing seal predation on salmon if specialist seals, which made up the majority of seal abundance in the gauntlet most days, were more successful on average at targeting salmon than non-specialist seals. If new information were available suggesting this to be the case, this model could be adapted to represent heterogeneity in foraging success and evaluate the impact on management efficacy. Similarly, we do not include an age or sex structure for pinnipeds, which could influence salmon consumption estimates, though recent work has found that sex-based diet differences in harbor seals were mostly due to differences in distribution and available prey than preference or skill (Conwell et al. 2024).

This paper describes an agent-based modeling framework that can be used to evaluate the impacts of predator management scenarios on the learning and foraging behavior of the predator, and their impact on prey species. With this tool we were able to identify that predator management in pinniped-salmon gauntlet systems will need to be frequent and fear-inducing to be the most effective, though even low levels of management effort in some systems could produce observable benefits to salmon recovery. Tribal managers and fishers currently have the ability and interest to implement management that aligns with these characteristics in many systems in Puget Sound but seek cooperation from federal agencies to ensure alignment with federal policies and legislation. This type of pinniped management would result in the greatest benefits for salmon, would align with the conservation principles of the MMPA by requiring fewer takes to reach escapement goals, and would support the culture and sovereignty of the treaty tribes of Washington State.

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Chapter 2 Appendix

Appendix 1: Subscript table

Subscript	Definition
t	time, loop day
i	individual pinniped index
l	foraging location (Gauntlet: l=1, not Gauntlet: l=0)
k	fear conditioning cue (1 = boats, 2 = hunt activity, 3 = gauntlet context)

Appendix 2: Variable table

Symbol	Parameter	Description
O_t	Gauntlet salmon	Abundance of each run of salmon at the Gauntlet as evaluated numerically in Equation 1 on day t
$O(T)$	Gauntlet salmon	Abundance of each run of salmon at the Gauntlet as evaluated for continuous time
$N_{t,l}$	Pinniped source pool abundance	Number of pinnipeds in the source pool. Subscript l indicates foraging location and separates Gauntlet (l = 1) from not Gauntlet individuals (l = 0) each day.
P_{ti}	Prob gauntlet overall	The probability that an individual pinniped will go to the Gauntlet to forage
X_{ti}	Learning term for foraging	Variable that keeps track of an individual’s perception of the fitness of the foraging opportunities at the Gauntlet
Y_{ti}	Learning term for fear	Variable that keeps track of an individual’s association between cues at the Gauntlet and fear about hunting risk
c_{ti}	salmon consumed by an individual pinniped	Calories of salmon (of all runs) consumed by an individual pinniped

H_t	total harvest	Number of pinnipeds of each species lethally removed in the Gauntlet
R_{ti}	receptivity to social information	term used to moderate the influence of social information to account for the strength of individual experiences with success or fear
η_{ti}	social information	an average of the P_{ti} for the individual's social circle S
$\hat{y}_{ti}$	predicted Gauntlet harvest risk	an individual's predicted risk associated with the Gauntlet based on cue associations
β_{tik}	association weight	association weight for each cue associated with Gauntlet harvest risk

Appendix 3: Parameter table

Symbol	**Parameter**	**Description**
A_{ts}	Arriving salmon	Number of salmon from each run entering the Gauntlet on day t
F_{ts}	Fishing mortality rate	Instantaneous fishing mortality rate. Salmon day^{-1}
B_{ts}	Harvest effort rate	Measure of harvest effort, as # boats participating out of the max possible for that system
E_{ts}	Escape Rate	Escape rate for each run of salmon. Salmon day^{-1}
M	Natural mortality rate	Mortality rate of salmon in the Gauntlet that is not accounted for in fishing or consumption by pinnipeds. Includes disease and other predation
u	baseline value for x or y	baseline value of X or Y that represents a naïve individual and that X and Y decay back to after long non-Gauntlet exposure

z	width of the Receptivity curve	the width of the receptivity curve for X or Y (same for both)
θ	maximum receptivity	the maximum receptivity value
σ	speed of learning about foraging at Gauntlet	describes the speed that the learning term X approaches the min and max values after each exposure to new information at the Gauntlet. i.e. if $\sigma = 0.25$ then X moves ¼ of the way closer to the max value after a positive reinforcement experience.
d	speed of forgetting about foraging while away from Gauntlet	describes the speed that the learning term X approaches the baseline values after the individual forages away from the Gauntlet. i.e. if d = 0.5 then X moves half the distance to the baseline after the individual forages away from the Gauntlet.
w	energetic cost	Amount of salmon in kcal that the individual might have been expected to consume outside the Gauntlet
L	learning rate for cue association	the rate at which cue association weights change according to exposure trials
ρ	decay rate for cue association weights	the rate at which cue association weights decay in the absence of presentation
r_{tk}	cue presentation	term that indicates whether cue k was presented (1) or not (0)
h	Hunt efficiency	term that describes the efficiency of hunters taking predators within range
g	Predator harvest spatial overlap	Spatial overlap between predators and hunting activity
τ	saturation	maximum salmon consumption for an individual pinniped species and salmon run combo based on caloric content and requirements

$\boldsymbol{\alpha}$	search and capture	search and capture rates for each pinniped species and salmon run combination based on catchability and preference
$\boldsymbol{\phi}$	forage location	decision about where to forage from a Bernoulli draw on the individual's P_{ti}

Chapter 3 Tribal pinniped harvest can improve adult salmon survival in terminal areas

Introduction

Increasing conflict between fisheries and recovering marine mammal populations has created an urgent interest in finding effective management strategies to mitigate the impacts of marine mammal populations on the conservation status of their prey populations (Punt and Butterworth 1995; Yodzis 2001; Trzcinski et al. 2006; Plaganyi and Butterworth 2008; Washington State Academy of Sciences 2022). This task poses multiple layers of challenges: the ecological uncertainty that comes from predicting changes to multispecies trophic interactions, the legal challenges posed by managing protected marine mammals to benefit their prey (some of which are also protected), and the socio-political implications associated with harassing or lethally removing charismatic megafauna (Courchamp et al. 2003; Treves and Karanth 2003; Rogers and Plagányi 2022). Models are a powerful tool for exploring uncertainty, constructing explicit management scenarios for consideration, and providing a theoretical world where creative and collaborative thinking about complex problems can occur (Gregory et al. 2001; Punt and Donovan 2007; Preikshot 2008; Epstein 2008). These strengths are why models have been used by managers in ecosystems around the globe to evaluate actions to address marine mammal conflict with fisheries (Punt and Butterworth 1995; Yodzis 1998; Trzcinski et al. 2006; Chasco et al. 2017; Haro et al. 2025).

In the Pacific Northwest, pinniped populations have been increasing since the passage of legislation in both the United States and Canada that protects marine mammals from disturbance and exploitation (Roman et al. 2013). Successfully recovered pinniped populations in the region (Jeffries et al. 2003; Wiles 2015; Laake et al. 2018; Pearson et al. 2024) are now implicated in the declines of multiple commercially and culturally important fish species in the region, such as Pacific herring, *Clupea pallasii*, (Schweigert et al. 2010) and Pacific salmon, *Oncorhynchus spp.*, (Wargo Rub et al. 2019; Washington State Academy of Sciences 2022). The Marine Mammal Protection Act of 1972 (16 U.S.C. § 1361 et seq.) in the United States has succeeded in recovering marine mammal populations because of its strong protectionary stance, but now this lack of flexibility has impeded the implementation of effective ecosystem management by preventing the adaptive management of pinniped populations. The conflict between pinnipeds and fisheries in the Pacific Northwest also exists in the context of the reserved rights of Tribes, arising from the Stevens Treaties of 1854 and 1855, to harvest their resources – including both pinnipeds and fish. The long history of conflict between government agencies, academia, and Indigenous nations means that the technical conversations about ecological uncertainty and specific harvest management regimes that need to happen to resolve this issue have been infrequent and contentious.

On a regional scale, most of our uncertainty about the potential impact of pinniped management stems from a lack of understanding of the magnitude and direction of the many trophic relationships that directly and indirectly shape the impact of pinniped predators on their prey (Trzcinski 2020; Washington State Academy of Sciences 2022). Recent studies have explored the impact of pinniped predators on survival of salmonids, the efficacy of potential large-scale management actions, and the uncertainty surrounding the multiple trophic pathways that link pinniped predators to their salmonid prey at multiple life stages (Chasco et al. 2017; Nelson et al. 2019; Walters et al. 2020; Moore et al. 2024; Couture et al. 2024). While ecosystem models can be useful for exploring these uncertainties and identifying regional trends, they are not necessarily intended to simulate the dynamics occurring on the finer spatial scale at which tribal management and resource use takes place (Preikshot 2008).

On a local scale, tribal fishers and managers express concern about the prevalence of pinnipeds in individual river systems where returning adult salmon are especially vulnerable to predation (Cram et al. 2018; Washington State Academy of Sciences 2022; Mulvihill-Kuntz et al. 2024). Because of the legal frameworks that govern treaty rights and responsibilities in Washington State, tribal members are only able to access resources using their treaty right within the boundaries of their adjudicated Usual and Accustomed areas (U&A) (Clark 1985). This means that regional conversations about pinniped management in the Salish Sea may not be relevant to inform management actions taken at a specific river system or within the U&A of a specific Tribe. Addressing these impacts on the scale of individual watersheds is critical to ensuring the survival of salmon runs, as illustrated by the functional extirpation of winter-run steelhead (*Oncorhynchus mykiss*) in the Lake Washington watershed due to predation by California sea lions (*Zalophus californianus*) at the Hiram M Chittenden Locks in Ballard, WA (Cram et al. 2018; Mulvihill-Kuntz et al. 2024). At this scale, the impact of pinniped predation on diminishing salmon harvest is felt by Tribal fishers, and the loss of salmon runs is an irreparable harm to communities, Tribal culture, and to the local ecosystem (Walsh et al. 2020).

This project used a Participatory Modeling Process (PMP) to develop a modeling tool to bridge the gap between current knowledge about the ecological impacts of pinniped predation and proposed management scenarios down to the level of individual river systems under tribal co-management. The PMP provides a framework for rights-holders, resource users, and local experts to shape the research objectives, model structure, data inputs, and utility of results. For this project, the process involved convening a group of experts from universities and tribal, state, and federal management agencies at a series of workshops to solicit opinions about high-priority research objectives and collaboratively develop a modeling tool to address the identified objectives. The research objective of this modeling tool was to enable managers to compare pinniped management strategies and assess their impact on the survival of salmon returning to their natal spawning grounds. We built an agent-based model of pinniped predation on salmon in “gauntlets” and simulated the outcomes of alternative pinniped management scenarios. We then used the model outcomes to (1) identify which measures are robust to uncertainty in the underlying predation dynamics; (2) identify what ecological conditions must be met for alternative control measures to be effective; and (3) identify key gaps that could be addressed through well-designed monitoring programs or future research efforts.

Methods

Model Overview

A detailed description of the model structure and dynamics is available in Chapter 2. The model uses agent-based components to simulate individual learning, fear conditioning, and decision-making by pinnipeds that are deciding whether to forage at the Gauntlet each day. Gauntlets are defined by three criteria: 1) the prey species migrates through the gauntlet, producing a temporally pulsed prey field; 2) there is some barrier or challenge to the movement of the prey that causes them to be constrained; and 3) the predator has access to the prey while they navigate this constraint. We simulate salmon movement and mortality on a continuous-time basis and use a flexible model that accounts for both prey- and predator-dependence to estimate consumption by pinniped predators. The model does not incorporate age-, size, or sex-structure of either the prey or predator because our primary objective is to explore within-season impact of management on a specific life stage of prey. Workshop participants encouraged modeling efforts to focus on adults approaching terminal areas instead of other life stages of salmon because of the uncertainty associated with attempting to account for compensatory mortality at other life stages (Washington State Academy of Sciences 2022) and due to the importance of adult returns for the productivity of salmon populations. The model is evaluated on a daily timestep for a single salmon migration season to explore dynamics of deterrence and foraging on short timescales and small spatial scales that match those of tribal fisheries management decisions. In this paper, we describe the parameterization of the model to simulate two case study systems and potential harvest regimes in each. The primary question that we asked was whether any of the candidate pinniped harvest scenarios in each case study had the potential to improve adult salmon survival through the gauntlet.

Case Study Locations

We focused model exploration on two gauntlet case study areas in Washington State, the Nisqually River and the Hiram M. Chittenden Locks (Ballard Locks) (Figure 3.1). Both of these systems are areas where salmon are forced to slow down during their migration and are therefore especially vulnerable to predation by pinnipeds (Brown and Mate 1983; Mulvihill-Kuntz et al. 2024), though the characteristics of each gauntlet and the way that salmon and pinnipeds interact there are very different. In both gauntlets, one of the challenges they must navigate is the process of osmoregulation to prepare for the transition from saltwater to freshwater (Hasler et al. 2011). At the Locks this transition is very abrupt, while the restored estuary in the Nisqually River likely helps mitigate this challenge by providing more complex habitat as shelter (Goetz and Quinn 2019; Urgenson et al. 2021).

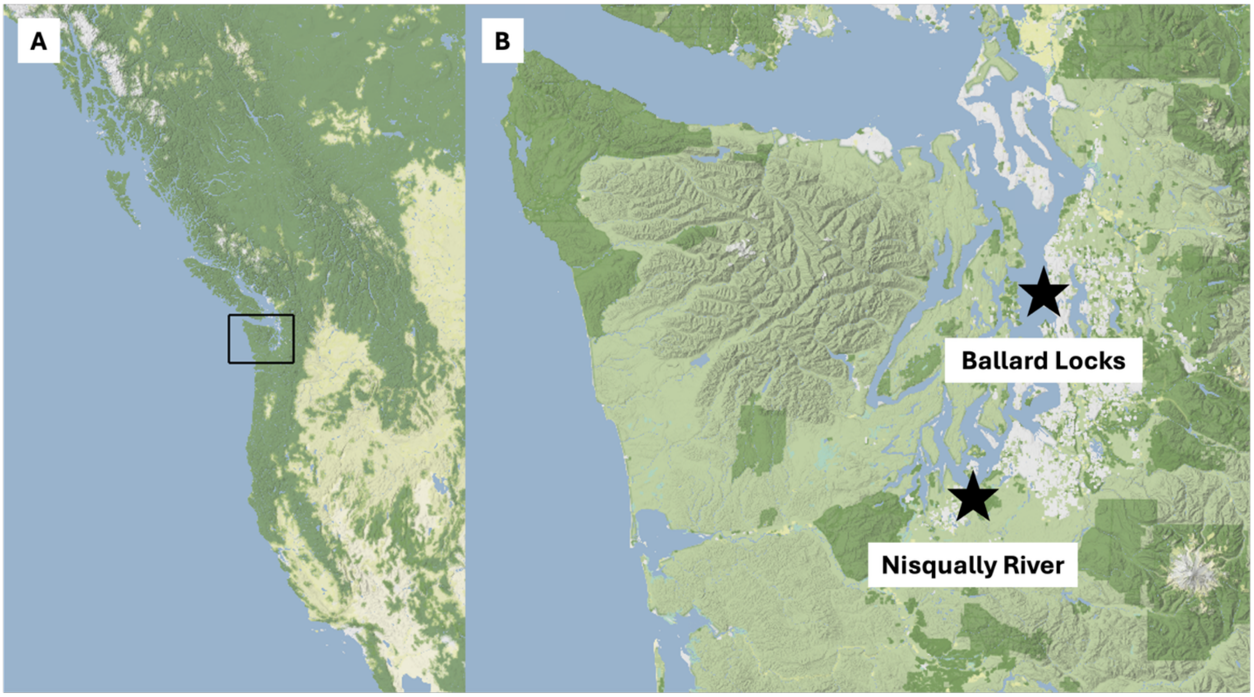

Figure 3.1: Map of gauntlet case study locations within the Puget Sound, WA. Panel A shows Western Washington situated within the West Coast of North America. Panel B shows the case study locations within Puget Sound.

Nisqually River

The Nisqually River is managed primarily by the Nisqually Indian Tribe and flows through the Tribe's Reservation and U&A (Medicine Creek Treaty, 1854, 10 Stat. 1132. Ratified Mar. 3, 1855). The Nisqually River gauntlet includes an extensive naturally vegetated delta that is protected as part of the Billy Frank Jr National Wildlife Refuge at Nisqually. The area upriver rapidly narrows into a single natural river channel restricted by the I-5 bridge crossing infrastructure and bordered by a patchwork of lands under tribal, military, and private landowner control (Figure 3.2). In this study, the gauntlet was defined as beginning at the river mouth and ending at the I-5 bridge crossing. This incorporates roughly the first 2.5 river miles.

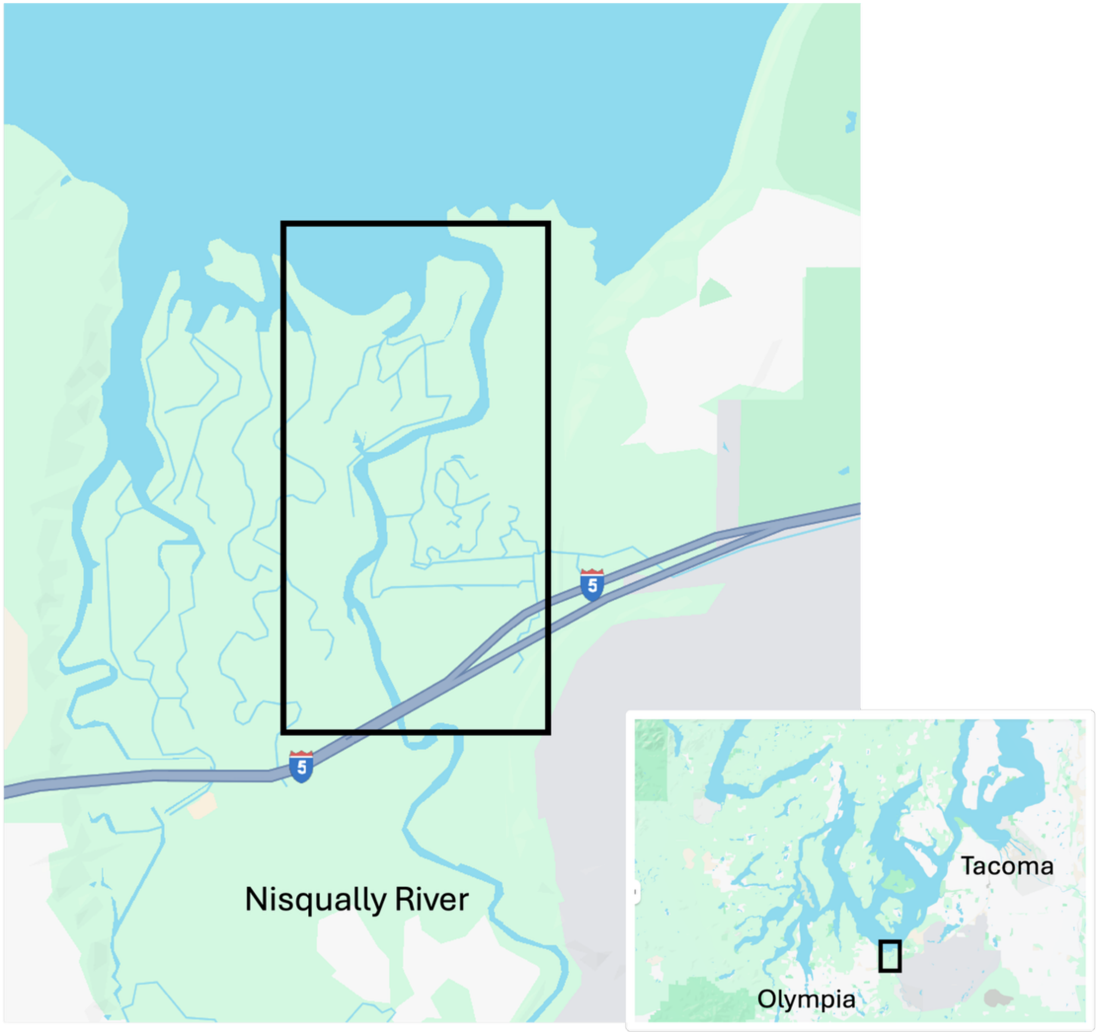

Figure 3.2: Map of the Nisqually gauntlet boundaries situated within the first 2.5 river miles of the Nisqually River, which flows into south Puget Sound, WA. Black box shows the boundaries of the gauntlet area.

We included three runs of salmon: winter Chum salmon (*Oncorhynchus keta*), wild Chinook salmon (*Oncorhynchus tshawytscha*), and hatchery Chinook salmon (from the Clear Creek and Kalama Creek hatchery programs, hatchery stock originally from the Green River). Coho salmon

(*Oncorhynchus kisutch*) were not included, despite their presence in the river, due to a lack of necessary data to parameterize their presence in the gauntlet. The winter Chum salmon run is ecologically unique to the region and culturally important to the Nisqually Tribe due to their late return timing (roughly November – January) compared to other fall-running Chum salmon in the Puget Sound basin (Pierce County Public Works & Utilities Water Programs Division 2005). Since Chum salmon spawn in the lower reaches of river systems, they must carry out two vulnerable life stages within the gauntlet: the physiological process of transitioning from saltwater to freshwater and the energy-intensive process of preparing to spawn. Chinook salmon returning to the Nisqually River in the fall are part of the ESA-listed Puget Sound ESU, and the hatchery fish are part of enhancement efforts to aid recovery and support the Tribe's treaty fishing right.

The pinniped dynamics in this system show strong seasonal patterns. For over a decade, California sea lions and Steller sea lions (*Eumetopias jubatus*) have been abundant during the winter Chum salmon run and largely absent during the rest of the year. Predation by sea lions was reported by Nisqually biologists in the main channel of the river sometimes more than 13 miles upriver (Walker Duval, personal communication 2023). Sea lions were observed using a sunken and abandoned barge near the mouth of the river within the National Wildlife Refuge as a primary haulout (Jed Moore, personal communication 2023). The Nisqually gauntlet system also featured year-round harbor seal (*Phoca vitulina*) abundance. Harbor seals utilized many fractured haulouts distributed throughout the side channels of the delta (Jeffries et al. 2000). They were mainly observed predating on salmon in the smaller side channels while sea lions were present, and throughout the delta when sea lions were not present (Craig Smith, personal communication 2023). They were sometimes observed more than 4 miles upriver, particularly when salmon were actively spawning (unpublished data, Nisqually Indian Tribe).

Recent work has quantified the impact of harbor seals on out-migrating steelhead smolts (Moore et al. 2024). This research has drawn attention to the degree of predation by pinnipeds that is being exerted on these stocks and the implications for fisheries and the fishers that rely on them. The Tribe’s Chum salmon fishery has been open for two of the last 10 years due to conservation concerns. Managers have documented that migration of winter Chum salmon has occurred earlier as pinniped predator abundances have increased (Agha et al. 2021). While the direct mortality impact of pinnipeds on returning adult Chum salmon abundance has yet to be quantified, managers have noted that the productivity of the Chum salmon population declines with the arrival of the large abundance of predators (Howard 2023). The large abundances of predators in the river when salmon are migrating and fisheries would be occurring is a source of frustration and concern for fishers and managers.

Ballard Locks

The Hiram M. Chittenden Locks (commonly referred to as the “Ballard Locks”; hereafter “Locks”) were constructed in 1917 as part of the creation of a ship canal from Lake Washington to the Puget Sound which re-routed rivers and salmon migration routes throughout the watershed. The Locks gauntlet is created by this channelized ship canal which leads from the Puget Sound to Lake Washington and includes a fish ladder that allows fish passage over the structure of the Locks (Figure 3.3). The freshwater side of the Locks leading into the Lake Washington watershed is located in the U&A of the Muckleshoot Tribe. The Tribe has been leading pinniped management efforts within their U&A (Treaty of Point Elliot, 1855, 12 stat. 927. Ratified Mar. 8, 1859), with varying involvement from state and federal agencies at the Locks for the last four decades (Mulvihill-Kuntz et al. 2024). The saltwater side of the Locks are within the adjudicated boundaries of the Suquamish Indian Tribe’s U&A (Treaty of Point Elliot, 1855, 12 stat. 927. Ratified Mar. 8, 1859). The Suquamish Indian Tribe did not participate in the creation of the Ballard Locks case study, so their fisheries, which occur in their U&A on the saltwater side of the Locks, were not included in simulation of fishing mortality or pinniped management. The Locks are owned and operated by the U.S. Army Corps of Engineers and are the most trafficked lock system in the United States. The surrounding area is operated as a public park and is visited by well over a million people annually as one of the most popular tourist attractions in Seattle (Corps Foundation 2025).

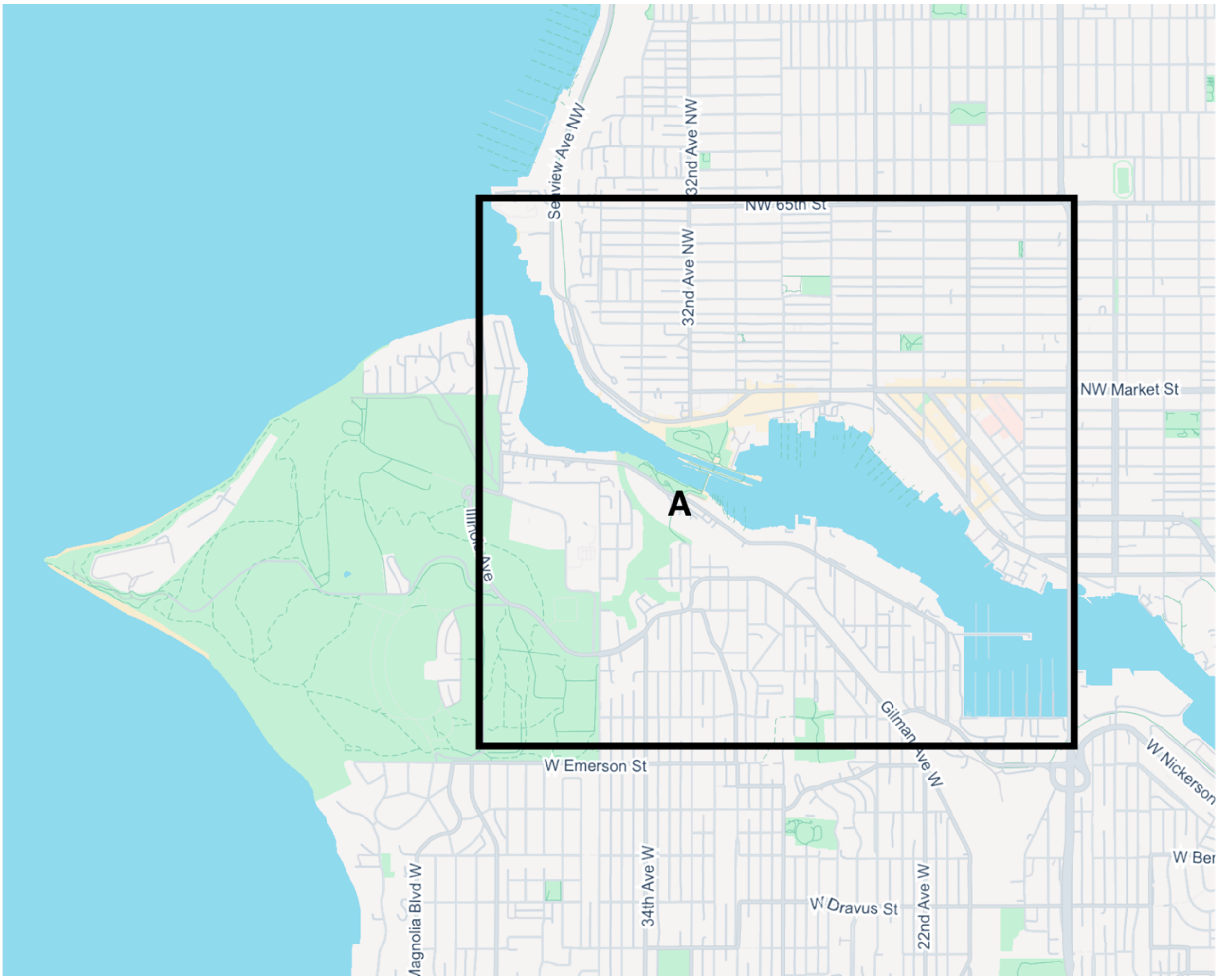

Figure 3.3: A map of the Ballard Locks gauntlet boundaries situated within the ship canal that leads from Puget Sound to Lake Washington in Seattle, WA. The black box indicates the boundaries of the gauntlet area. (A) the location of the fish ladder that leads through the Ballard Locks structure.

The ship canal is now the only migration route for salmon to pass between the freshwater and saltwater in this watershed, and it is used by three main extant salmon runs. Adult Sockeye salmon migrate through the ship canal between June – August, Chinook salmon return between July - September, and Coho salmon between August – October. Each salmon run encounters substantial migration barriers as they traverse the ship canal through the Locks. The Locks present an abrupt shift between cool Puget Sound saltwater and the freshwater of the ship canal, which often exceeds temperature thresholds for salmon stress and mortality in the summer months (Urgenson et al. 2021). The combined stressors of elevated temperatures and the transition from saltwater to freshwater causes fish to delay migration or cycle through the Locks repeatedly while they adjust to the change in salinity or wait for cooler temperatures, extending their exposure to pinniped predators (Goetz and Quinn 2019).

The nearest major pinniped haulouts are at Shilshole Marina and Elliott Bay Marina, both operated by the Port of Seattle, which are populated mainly by harbor seals and California sea lions. Harbor seals utilize the Locks gauntlet area year-round and were observed foraging near the Locks (on the saltwater and freshwater side), inside the Locks, and inside the fish ladder whenever salmon – adults or smolts – were migrating through the ship canal (Muckleshoot Indian Tribe, unpublished data). California sea lions mainly used these haulouts during the winter and spring but were not present in large abundances during the migration of adult Sockeye and Chinook salmon through the ship canal between June and September (Veirs et al. 2025). In the 1980's and early 1990's, predation on salmonids, particularly steelhead arriving in the springtime, by California sea lions at the Locks was rampant, but more recently the system is dominated primarily by harbor seals during peak adult salmon migration in the summer and fall (Mulvihill-Kuntz et al. 2024). Despite diverse and intensive management efforts for over four decades, pinnipeds have been implicated in the functional extirpation of Lake Washington winter-run steelhead, declines in Lake Washington Sockeye salmon, and lack of recovery for ESA-listed Chinook salmon (NMFS 2017; Cram et al. 2018; Mulvihill-Kuntz et al. 2024).

Case Study Parameterization

Salmon Inputs

In the case study model for each gauntlet, we simulated returning adult salmon abundance over time as governed by several processes: the influx of salmon arriving at the gauntlet, natural mortality, fishing mortality, pinniped predation mortality, and movement beyond the gauntlet ("escape"). Salmon arrival in the gauntlet was simulated based on data collected through tribally run hatchery or enhancement efforts in each system, counts from observations, and from fishery catch data (Figure 3.4, Figure 3.5). We simulated salmon movement beyond the gauntlet in each system based on residence time data collected through tagging efforts, fishery catch data or estimated by local experts. Fisheries catch rates were based on fisheries harvest data provided by collaborators. We estimated natural mortality terms from the literature. The models for each case study were parameterized to reflect the differences in case study locations by changing salmon arrival and residence time inputs, fishing effort, and natural mortality terms. We did not include pink salmon in the model, so it was not configured to simulate odd years when pink salmon would be returning to the Nisqually River system. In both case studies, we explored the uncertainty associated with the residence time parameter by running variants of the model with 20% higher and lower residence times for each salmon run.

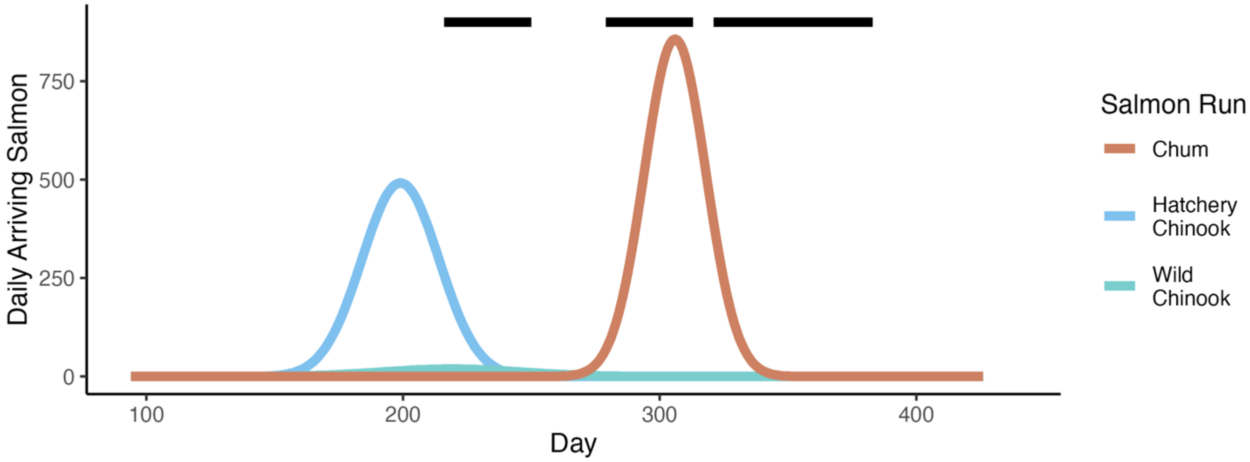

Figure 3.4: Salmon arrival curves for the Nisqually River. Black bars at the top of the plot indicate the approximate dates when the Chinook salmon fishery, Coho salmon fishery, and Chum salmon fishery (from left to right) occur.

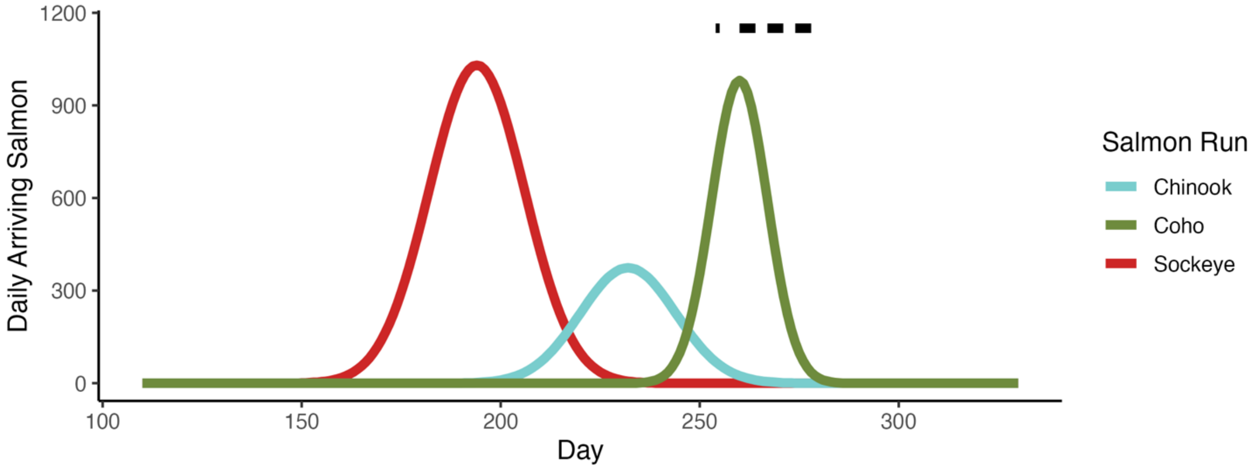

Figure 3.5: Salmon arrival curves for the Ballard Locks. The black lines at the top of the plot indicate the approximate dates of the Muckleshoot Indian Tribe's Coho salmon fishery which occurs in the freshwater side of the ship canal above the Locks.

Bioenergetic Parameters

This model was not designed to produce precise estimates of consumption of salmon in either of our case study systems, but rather to provide plausible and informed approximations to guide the assessment of predator management scenarios. To that end, we are interested in the difference in consumption between scenarios as an indicator of their success. To account for the uncertainty in actual consumption estimates, especially in niche habitats like the gauntlet, we compare management scenarios under two parameterizations to provide upper and lower bounds (High and Low parameterizations) on reasonable consumption behavior and illustrate the importance of continuing to research and monitor these systems in pursuit of better consumption estimates.

In each consumption parameterization, we tuned parameters according to different assumptions about the foraging behavior of pinnipeds in the gauntlet. In the Low consumption scenario, we assumed that salmon is only a fraction of the diet of pinnipeds even though there are very few other prey species available to pinnipeds when they forage at the gauntlet. In this parameterization, we use scat studies to inform the maximum daily consumption of salmon, τ_{ps} (Table 3.1; Equation 2). For harbor seals, Thomas et al. (2017) developed diet proportions using scats collected in estuary habitats near abundant salmon runs, a good gauntlet analog, and assigned diet proportions to each salmon species. Few diet studies on sea lions have been done recently in Puget Sound, so studies conducted on the Pacific coast were used to inform diet proportions (Scordino et al. 2022; Lewis 2022) as has been done in other regional estimates of consumption in Puget Sound (Chasco et al. 2017). These estimates come from an area characterized by coastal open water habitat through which salmon migrate to Puget Sound with no nearby productive salmon rivers. We acknowledge that the diet proportions used to produce the low consumption estimate for sea lions are likely an underestimate due to the difference in prey availability between the study regions and the gauntlet areas we were interested in simulating. Since the purpose of the diet proportion consumption estimate is to provide a lower bound, we tolerate this bias. A few studies have been done on Steller sea lions in Southeast Alaska and their relationship to temporally and spatially pulsed prey fields (Trites and Calkins 2007; Womble et al. 2009; Sigler et al. 2009; Tollit et al. 2015), which produce similar estimates of seasonal diet proportion made up by salmonids. The number of salmon required to meet the energy equivalent of a proportion of pinniped diet was rounded up to the number of whole fish that need to be captured for each pinniped to meet the designated proportion of their daily energetic requirements (Table 3.1).

Table 3.1: Maximum consumption values (parameter τ) in number of fish per day per individual predator for each pinniped species and salmon run combination in high- and low-consumption parameterizations.

Case Study	**Salmon Run**	**Consumption Parameterization**	**Harbor seal**	**California sea lion**	**Steller sea lion**
Nisqually River	Hatchery Chinook	High	1	7	10
		Low	1	1	1
	Wild Chinook	High	1	4	6
		Low	1	1	2
	Chum	High	2	11	18
		Low	1	3	4

Ballard Locks	Sockeye	High	2	11	17
		Low	1	1	1
	Coho	High	3	16	26
		Low	1	5	6
	Chinook	High	1	6	9
		Low	1	1	1

In the high consumption scenario, we assumed that pinnipeds foraging at the gauntlet have a preference for salmon as an energy-dense food and are likely to display certain foraging behaviors – such as belly-biting, gorging, incomplete consumption, and high-grading – that result in more salmon being killed than are needed to fulfill the pinniped's daily caloric needs (Gende et al. 2001; Hocking et al. 2017). In this scenario, the simulated maximum consumption level for each pinniped was three times the number of salmon needed to meet 100% of their daily caloric needs. In this case, we assume that this is the maximum number of salmon that were captured and can be consumed, though they may not be consumed completely if the predator was engaging in a foraging behavior that results in incomplete consumption, like belly-biting. The energy content of each salmon species was derived from published values and adjusted as possible according to the average size of fish from each run in our case study gauntlet systems (Harper 1980; Hendry and Quinn 1997; Gustafson et al. 1997; Winship and Trites 2003; O'Neill et al. 2014; Chasco et al. 2017; Goetz and Quinn 2019; Nisqually Indian Tribe and Washington Department of Fish and Wildlife 2024).

In both scenarios, we assumed that pinnipeds learn to associate the gauntlet with successful foraging conditions if they are able to consume more salmon than they might be expected to encounter outside the gauntlet during times of large returning adult salmon abundance (based on non-estuary and regional diet estimates such as (Olesiuk et al. 1990; Trites and Calkins 2007; Lance et al. 2012; Tollit et al. 2015; Thomas et al. 2017; Scordino et al. 2022). This baseline level of salmon consumption, expressed in kcal, informed the parameter w (Table 3.2; Equation 3).

Table 3.2: Daily energy requirements for each pinniped species and the diet data that informed parameter w, the baseline consumption of salmon per predator required for foraging success at the gauntlet.

	Harbor seal	California sea lion	Steller sea lion	References
Daily caloric requirement	14,849 kJ (3,549 kcal)	95,408 kJ (22,803 kcal)	150,001 kJ (35,851 kcal)	(Winship and Trites 2003; Chasco et al. 2017)
Baseline Salmonid % Diet	10.3%	13.1%	11.6%	(Olesiuk 1993; Tollit et al. 2015; Scordino et al. 2022)
Parameter w	366 kJ (366 kcal)	1,531 kJ (3,033 kcal)	17,401 kJ (4,159 kcal)	

We also expected the search and capture efficiency parameter α (Equation 2) to be unique for each pinniped-salmon species pairing due to differences in body size, foraging behavior, and swim speeds. For harbor seals, we expected Sockeye salmon and Chum salmon to be preferred and more easily captured prey based on scat studies and foraging observations (Thomas et al. 2017). For all pinniped species, we expected adult Chinook salmon to be a challenging prey item to capture and consume, but we assumed that California sea lions were most effective, and harbor seals were least effective (Hatch et al. 2018; Scordino et al. 2022). The population of wild Chinook salmon in the Nisqually River are larger on average than their hatchery counterparts, and we assumed they were also more difficult to capture for all three predator species (Nisqually Indian Tribe and Washington Department of Fish and Wildlife 2024). We account for these differences in the parameterization of the search and capture efficiency as described in Table 3.3 based on expert opinion and foraging observation studies that describe feeding in gauntlet analog sites or describe diet preferences in relation to prey abundance (Brown and Mate 1983; Thomas et al. 2017; Hatch et al. 2018).

Table 3.3: Instantaneous search and capture efficiency (per predator per day) values (parameter α) for each pinniped and salmon species combination (See Equation 2). The capture efficiency estimates were informed by expert interpretations of published studies during the participatory modeling process.

	Harbor Seal	Steller Sea Lion	California Sea Lion
Chinook	0.05	0.3	0.4
Wild Nisqually Chinook	0.03	0.2	0.26
Chum	0.3	0.5	0.6
Coho	0.1	0.4	0.5
Sockeye	0.3	0.5	0.6

We emphasize here that the bioenergetic parameters for both case study models were informed by the best available data for the system or for the next closest spatial area or scale. Parameterization of the models would benefit from additional studies to provide directly applicable parameter inputs for gauntlet areas.

Environmental Conditions Affecting Pinniped Predation

This model was not constructed to produce insights about the impact of environmental variables on salmon or pinniped behavior in the gauntlet. However, in both case studies there were specific environmental effects worth exploring. In the Locks, salmon migrating toward Lake Washington through the ship canal in the summer months frequently encounter elevated water temperatures that can cause them to spend more time at the Locks adjusting to the abrupt change in water conditions or waiting for more favorable temperatures (Urgenson et al. 2021). To understand the impact of elevated residence times on the effectiveness of pinniped management strategies, we developed a variation on the base run where residence times of all salmon species were increased by 50% during the period between July 1 and September 1. In the Nisqually River, higher flows beginning on October 1 drastically increase the volume and turbidity of the river. We expected this to decrease the search and capture efficiency of pinniped predators attempting to find prey in the gauntlet. To simulate this dynamic and understand the impacts of seasonal flow regimes on the effectiveness of pinniped management strategies, we decreased all α parameter values (search and capture efficiency; Equation 2) by 50% for each pinniped predator starting on October 1 in the Nisqually River case study.

Pinniped Learning Parameter Tuning

Parameter values for the Rescorla-Wagner learning model (Rescorla and Wagner 1972) that we used to simulate pinniped fear conditioning dynamics were informed by the literature. The learning rate (Equation 5 & Table 2.1) was set at 0.15 according to common practice and laboratory studies (Quirk 2002; Miller and Shettleworth 2007; Paskewitz et al. 2022). During iterative testing of this model with our collaborators, this value produced fear behavior in modeled pinnipeds at a speed that matched anecdotal behavioral observations from experts in each gauntlet system. The concept of using the same parameter for learning about fear and safety (both positive and negative change in association strengths) is also well supported in the literature, and enables the model to simulate the rapid fear response from pinnipeds and rapid return to locations where they have been exposed to fear once the source is no longer present (Schakner et al. 2017a; Tidwell et al. 2021). In Chapter 2, we explored the model sensitivity to the memory decay parameter ρ (Equation 5 & Table 2.1) and found that it was not an influential parameter on the model output. Widely varying values were used in the literature, but a value of 0.05 for this model produced dynamics that simulated observed pinniped behavior patterns in the region. Specifically, the inclusion of a small value for ρ allows pinnipeds to continue to fine-tune their cue associations to react strongly to harvest activity and accurately discern between harvest activity and other cues associated with the gauntlet.

Social Association Network

Previous studies in the Columbia River have quantified the degree of social association between California sea lions and the spread of gauntlet specialist behaviors through their social networks (Schakner et al. 2016, 2017b). We simulated a social network for each pinniped species with a similar degree of connectivity between individuals as the network developed by Schakner et al. (2016). Individuals that are associated learn from each other’s foraging decisions, as described in greater detail in Chapter 2 (Equations 8 – 10).

Base Scenario

In the Base Run we simulate the absence of pinniped management actions. The Base run scenario for both case studies was parameterized as described in Table 3.4. We chose these parameter values to produce model behavior that matched observations of pinniped abundance and behavior in each system when salmon were abundant. For the Nisqually River, we tuned the model to produce approximately 40 harbor seals, 50 California sea lions, and 15 Steller sea lions in the gauntlet daily during peak pinniped abundances. Harbor seals are present year-round, but both California and Steller sea lions arrive at the Nisqually River in anticipation of the arrival of the winter Chum salmon on December 1. Accounting for observer error and the potential for visitation by multiple individuals over the course of the day, we tuned the model to produce peak gauntlet abundances of around 30 harbor seals per day. This number was estimated by expanding upon unofficial observation counts that occur in a portion of the gauntlet (Muckleshoot Indian Tribe, unpublished data). Sea lion abundance was generally low in the summer as most California sea lions leave the region during the summer and return in the fall (Wright et al. 2010; Gearin et al. 2017; Veirs et al. 2025). We included 20 California sea lions at the beginning of the model until June 1st, then removed them from the model during the summer, and reintroduced a subsample of 5 that returned on August 25th and stayed in the source population until the end of the model.

Table 3.4: Pinniped parameterization for the foraging learning and fear conditioning aspects of the model. A full parameter table can be found in Chapter 2 Appendices 1-3.

Parameter	**Description**	**Naïve Harbor Seal (Specialist)**	**California Sea Lion**	**Steller Sea Lion**
X_{base}	Baseline X value	0.001 (0.1)	0.1	0.1
z	Width of the Receptivity curve	15	15	15
θ	Height of the Receptivity curve	√0.5	√0.5	√0.5
σ	Foraging learning rate	0.05 (0.3)	0.3	0.3
d	Foraging memory decay rate	0.1	0.1	0.1

L	Fear cue association learning rate	0.15	0.15	0.15
ρ	Fear cue association decay rate	0.05	0.05	0.05

Pinniped Management Scenarios

Pinniped Management Inside the Gauntlet

We created predator management scenarios that were tailored to each of our pinniped-salmon gauntlet case studies (Table 3.5). We constructed management scenarios according to two legal routes for the lethal removal of pinnipeds in Puget Sound: 1) tribes with treaty-reserved fishing rights can exercise those rights through the removal of individual pinnipeds that are deemed to be a threat to gear, catch, or human life; or 2) the federal government, or state governments via delegated authority, can remove nuisance animals under Section 120 of the Marine Mammal Protection Act of 1972. While the details of these pathways are complex, we chose a few key characteristics that were most relevant to each case study to explore in this analysis: the fear potential of removals and the timing of removals. Under the first legal pathway, lethal removals would occur via boat-based hunting with a firearm which would result in a fear response from other pinnipeds in the vicinity (Schakner et al. 2017a). At the moment, removals to protect gear, catch, and life can only occur during active fishing operations, though there is the potential for the National Marine Fisheries Service to expand this authorization beyond this temporal limitation to protect catch proactively by protecting salmon abundance from pinniped predators. Tribes could also gain this type of expanded pinniped management authority through a waiver of the take moratorium under Section 104 of the MMPA, which would enable tribal managers to revive pinniped hunting practices and utilize the impact of those harvests on pinniped distribution and abundance to achieve salmon conservation objectives. Under the second legal pathway, lethal removals would occur via trapping and offsite chemical euthanasia, which would not result in a fear response from other pinnipeds in the vicinity. The available management resources would limit the scale of implementation for trapping efforts.

To explore the potential impact of applying ecology of fear principles in management regimes via the "protection of gear and catch" legal pathway, we constructed scenarios in each system that involved boat-based harvest of pinnipeds. We evaluated the relative benefits of conducting this type of management in two discrete time windows: during the entire time when salmon are present at the gauntlet, or during fishing operations only. Boat-based harvest scenarios also differed in efficiency depending on whether the practitioners focused on pinniped removal efforts or were removing pinnipeds opportunistically during otherwise dedicated fishing activity. In the Nisqually River, this translated into a scenario for lethal removal during the Coho salmon and Chinook salmon fisheries ("Fishing"), a scenario that added lethal removal during the Chum salmon fishery ("Fishing + Chum"), and a scenario where dedicated harvest could occur during any days when fish were migrating through the gauntlet ("Expanded"). At the Locks, we developed a scenario for lethal removal during the Coho salmon fishery in the freshwater side of the ship canal ("Fishing"), a scenario that allowed dedicated take during any day that fish were present but only above the Locks on the freshwater side of the ship canal ("Limited"), and a scenario that allowed dedicated take throughout the gauntlet during any day that fish were present ("Expanded").

To explore the trapping and euthanasia option that is described in the MMPA, we developed a management scenario for the Locks that aimed to remove a set number of individual California sea lions bi-weekly during the entire model duration. We did not include trapping of harbor seals because they are not effectively targeted through this management strategy. This scenario did not impact the fear conditioning mechanism of the model since the sea lions were assumed to be removed discretely and euthanized offsite.

Table 3.5: Descriptions of pinniped management scenarios for both case studies

Case Study	Scenario	Description
Nisqually River	Fishing	Pinniped lethal removal occurs incidentally during the Coho salmon and Chinook salmon fisheries

Nisqually River	Fishing + Chum	Pinniped lethal removal occurs incidentally during the Coho salmon, Chinook salmon, and Chum salmon fisheries
Nisqually River, Ballard Locks	Expanded	Dedicated pinniped lethal removal activity occurs throughout the gauntlet during every day that salmon are present
Ballard Locks	Fishing	Pinniped lethal removal occurs incidentally during the Coho salmon fishery in the freshwater side of the ship canal above the Locks
Ballard Locks	Limited	Dedicated pinniped lethal removal activity occurs during every day that salmon are present only above the Locks on the freshwater side
Ballard Locks	Trap	California sea lions are removed on a regular schedule via trapping and euthanasia, as would occur under Section 120 of the MMPA. This scenario does not result in fear conditioning.
Nisqually River, Ballard Locks	Haulout	The simulated source population is reduced by 50%. For the Nisqually River case study, this might occur via removing the derelict barge at the mouth of the river, resulting in a 50% reduction in sea lion source populations that use it but not affecting the harbor seal source population. For the Locks, this might occur via the implementation of better deterrence at the nearby marina haulouts, which would affect all pinniped source populations. This scenario could also simulate a situation where 50% of each pinniped population is lethally removed, though there is no clear legal pathway for that at present.

Pinniped Management Outside the Gauntlet

We also considered scenarios of predator management that resulted in a smaller source population because of activities that happened outside the gauntlet (referred to as “Haulout”). At the Nisqually River, we simulated this strategy for both sea lion species to approximate the removal of the abandoned barge that sea lions use as a major sea lion haulout at the mouth of the river. At the Locks, we used this strategy to simulate more effective deterrence of harbor seals from artificial haulouts in and around Shilshole and Elliott Bay marinas. In both case studies, we reduced the overall source population of predators by a reduction factor (25%, 50%, 75%) before running the model and allowed those removals to disrupt the existing social association network for the population. We assume for all scenarios that no immigration or emigration occurs in the source population during the model run.

We ran all management scenarios for 20 replicates with the same parameters and saved relevant variables from each replicate to assess model behavior and compare outputs. While this number of replicate runs does not allow us to precisely detail the range of likely outcomes for each scenario, it is sufficient for a comparison of means.

Results

Base Runs

In both case studies we were able to replicate expected patterns of pinniped gauntlet attendance and salmon movement using the modeling framework presented here (Figure 3.6, Figure 3.7).

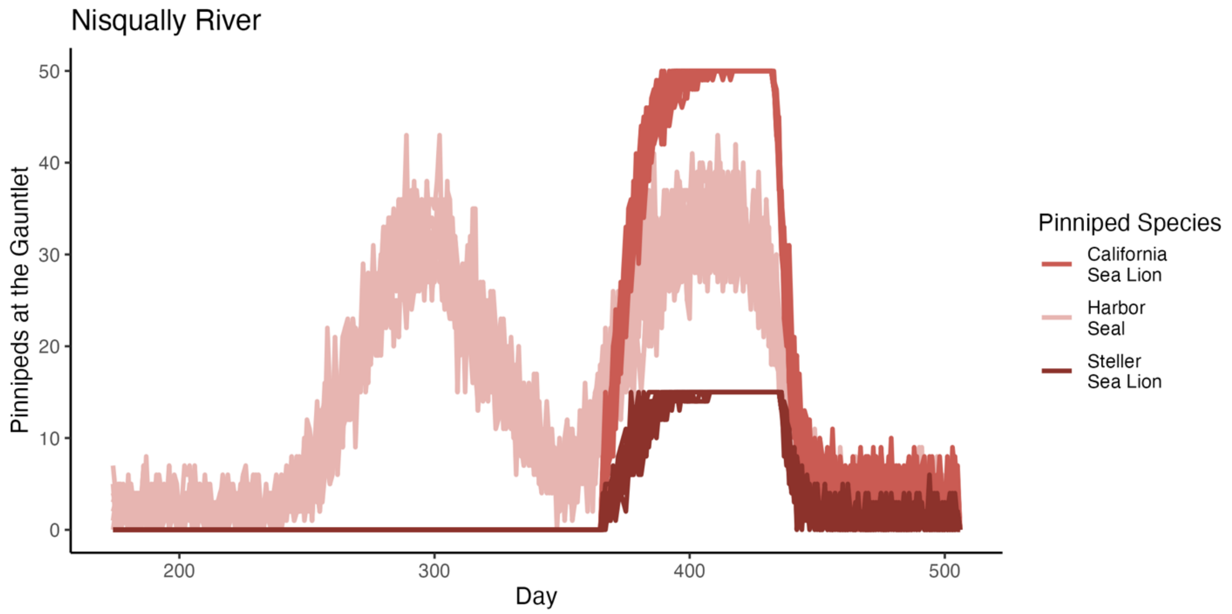

Figure 3.6: Daily pinniped attendance at the gauntlet during base run scenario replicates for the Nisqually River case study. Each line depicts the daily abundance of each pinniped species that chose to forage in the gauntlet over 20 model replicates.

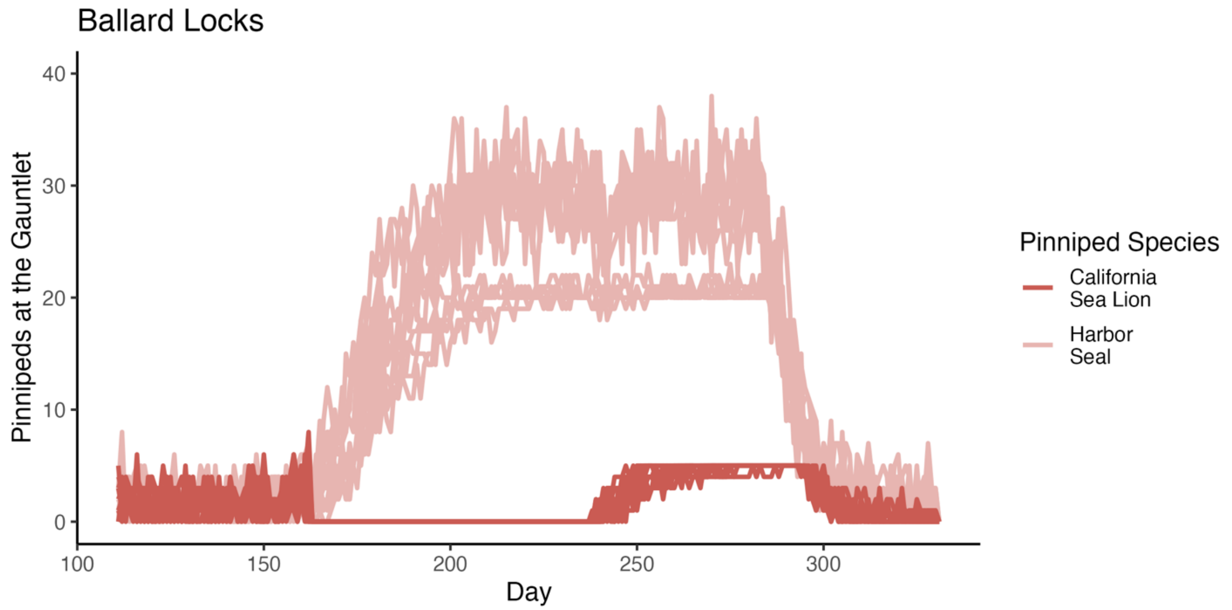

Figure 3.7: Daily pinniped attendance at the gauntlet during base run scenario replicates for the Ballard Locks case study. Each line depicts the daily abundance of each pinniped species that chose to forage in the gauntlet over 20 model replicates.

These baseline patterns of pinniped attendance at the gauntlet produced a range of predation impacts across sites and salmon runs (Table 3.6). The largest impact was for Chum salmon in the Nisqually case study, where on average, 37% of the run was consumed by pinnipeds in the base model. In comparison, a relatively small percentage of the sockeye run at the Ballard locks (ca. 4%) was consumed by pinnipeds in the base run. Four of the six runs were simulated to have more than 10% consumed by pinnipeds. In all subsequent results, we compare salmon predation rates under alternative pinniped control scenarios to these baseline rates.

Table 3.6: Estimates of consumed and gauntlet-escaped adult salmon given base model parameterization for each case study.

Case Study	Salmon Run	Total Consumed (Inner 90% Quantile)	Total Gauntlet Escape	% Consumed
Nisqually River	Hatchery Chinook	1,562 (1,512 – 1,614)	16,938	8.4%
	Wild Chinook	162 (160 – 164)	1,138	12.4%
	Chum	9,549 (9,487 – 9,668)	16,251	37.0%
Ballard Locks	Sockeye	1,270 (978 – 1,379)	29,730	4.1%
	Chinook	1,682 (1,445 – 1,752)	9,573	14.9%
	Coho	2,003 (1,836 – 2,065)	15,222	11.6%

Management Scenarios

Impact on Salmon Predation Mortality

In both case studies, the Expanded scenario, where lethal removals were carried out via boat-based hunting activity during all days that salmon were in the gauntlet, produced the largest improvement in salmon survival for all salmon runs (Figure 3.8, Figure 3.9). In the Nisqually case study, none of the scenarios produced large improvements in survival for the two Chinook salmon runs, and the consumption of wild Chinook salmon run was particularly unresponsive to management. The winter Chum salmon run in the Nisqually was more responsive and benefitted notably from both the Haulout reduction and Fishing + Chum scenarios (Table 3.7). In the Locks case study, the Haulout reduction scenario produced the second highest improvement in salmon survival for all runs (Table 3.8). The Trap scenario reduced predation on the Coho salmon run but had no impact on the Sockeye salmon and Chinook salmon runs. The scenarios that only included management actions implemented on the freshwater side of the Locks (Fishing and Limited) were not effective at improving salmon survival for any of the salmon runs (Figure 3.9).

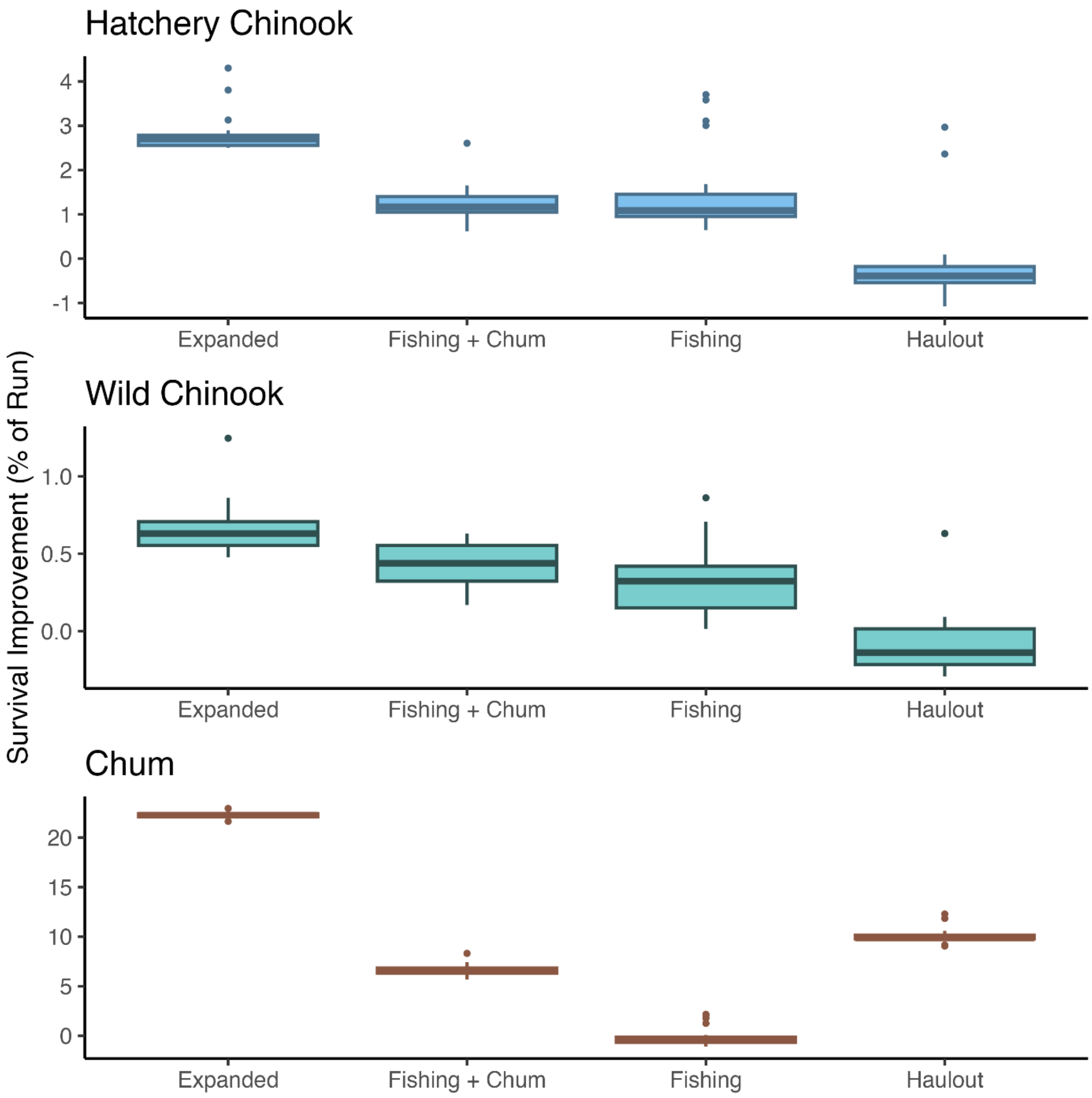

Figure 3.8: Boxplots showing the improvement in salmon survival, expressed as a percent of the total abundance of each run, under each management scenario simulated at the Nisqually River as compared to the Base (no take) scenario

Table 3.7: Average proportion of each run of salmon consumed by pinnipeds in each management scenario simulated at the Nisqually River.

	Base	**Fishing**	**Fishing + Chum**	**Expanded**	**Haulout**

Hatchery Chinook	8.4%	6.8%	6.7%	4.7%	7.7%
Wild Chinook	12.4%	11.9%	11.8%	10.8%	12.2%
Chum	37.0%	36.8%	15.5%	11.3%	25.7%

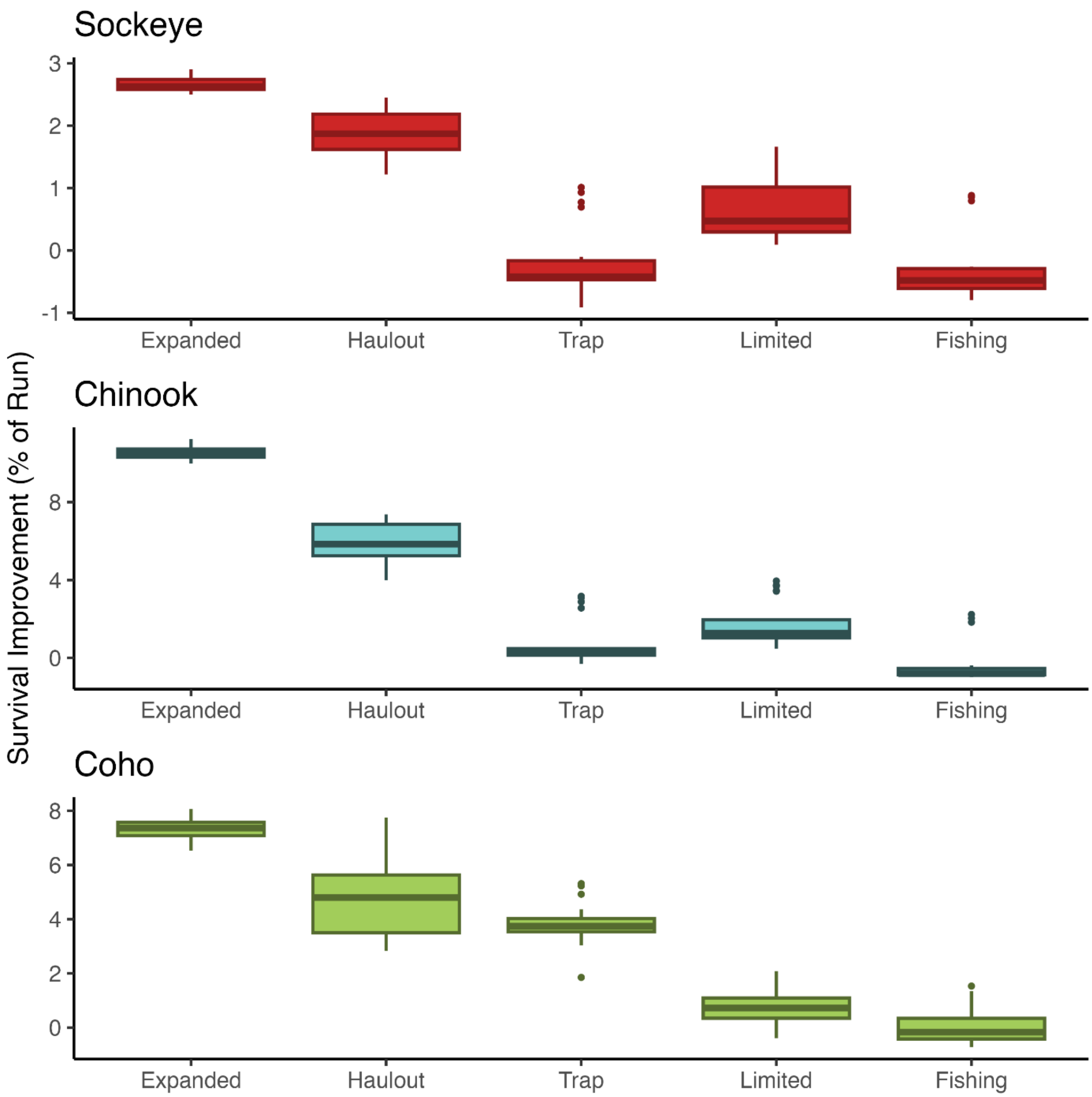

Figure 3.9: Boxplots showing the improvement in salmon survival, expressed as a percent of the total abundance of each run, under each management scenario as compared to the Base (no take) scenario

Table 3.8: Average proportion of each run of salmon consumed by pinnipeds in each management scenario simulated at the Ballard Locks

	Base	**Fishing**	**Limited**	**Expanded**	**Haulout**	**Trap**
Sockeye	4.0%	4.5%	3.3%	1.3%	2.1%	4.2%
Chinook	14.0%	14.7%	12.6%	3.8%	8.5%	13.6%
Coho	10.8%	10.8%	10.0%	3.5%	6.1%	7.0%

In both case studies, the most effective management scenario for each run was the scenario that targeted the pinniped species with the largest predation impact on that run. In the Nisqually River, the Chum salmon run would benefit from removing the barge haulout and reducing the presence of sea lions in the area while Chum salmon are migrating, but this scenario has no impact on either of the Chinook salmon runs that arrive to the system earlier before the sea lion abundance increases with the arrival of winter Chum salmon. Similarly, in the Ballard Locks case study the Trap scenario, which only impacts the abundance of California sea lions and not harbor seals, only produced improved survival outcomes for Coho salmon, which overlap temporally with the return of sea lions in the fall.

Management Effort and Pinniped Removals

Salmon survival is the main output that we use to compare management scenarios, but we also need to understand the relative amount of management effort and pinniped removals required to achieve improvements in salmon survival to fully understand the tradeoffs associated with each scenario. The Fishing scenarios resulted in few or zero pinniped removals for both case studies, but in the Nisqually River these scenarios were still able to achieve improvements in salmon survival because of the deterrent effect on pinniped use of the gauntlet (Table 3.9, Table 3.10). The Expanded scenarios resulted in the greatest improvements in salmon survival but also required substantial management effort and pinniped removals in both gauntlets.

Table 3.9: Summary of pinniped removals and active management days resulting from each management scenario in the Nisqually River case study.(*) Managers could achieve the benefits described by the Haulout scenario via lethal removals or by reductions in pinniped abundance in the gauntlet vicinity through non-lethal

means, such as removing available haulout space. Active management days are not applicable for the Haulout scenario since we simulate this scenario to occur outside of the modeled timeframe.

	Expanded	Haulout	Fishing + Chum	Fishing
# Harbor seals lethally removed	15	0*	0	0
# Sea lions (both California and Steller) lethally removed	42	30*	1	0
Active management days	232	NA	133	70

Table 3.10: Summary of pinniped removals and active management days resulting from each management scenario in the Ballard Locks case study. Removals denoted with an asterisk indicates where managers could achieve the benefits described either by lethal removals or by non-lethal reductions in pinniped abundance in the gauntlet vicinity such as removing available haulout space. Active management days are not applicable for the Haulout scenario since we simulate this scenario to occur outside of the modeled timeframe.

	Expanded	Haulout	Trap	Limited	Fishing
# Harbor seals lethally removed	23	50*	0	0	0
# California sea lions lethally removed	0	10*	9	0	0
Active management days	162	NA	15	162	19

Robustness to Parameter Uncertainty

Figure 3.10 and Figure 3.11 illustrate the wide range of plausible pinniped consumption values for each run under different model parameterizations developed to capture the uncertainty in key data inputs for each case study. By far, the simulated % of run consumed was highly sensitive to the choice of consumption values, as expected from Equation 2. In comparison, the other parameter scenarios did not drastically affect the simulated % run consumed. While none of these alternate parameterizations resulted in a change in the ranking of management scenario effectiveness, they did impact the overall effectiveness of management at reducing pinniped predation.

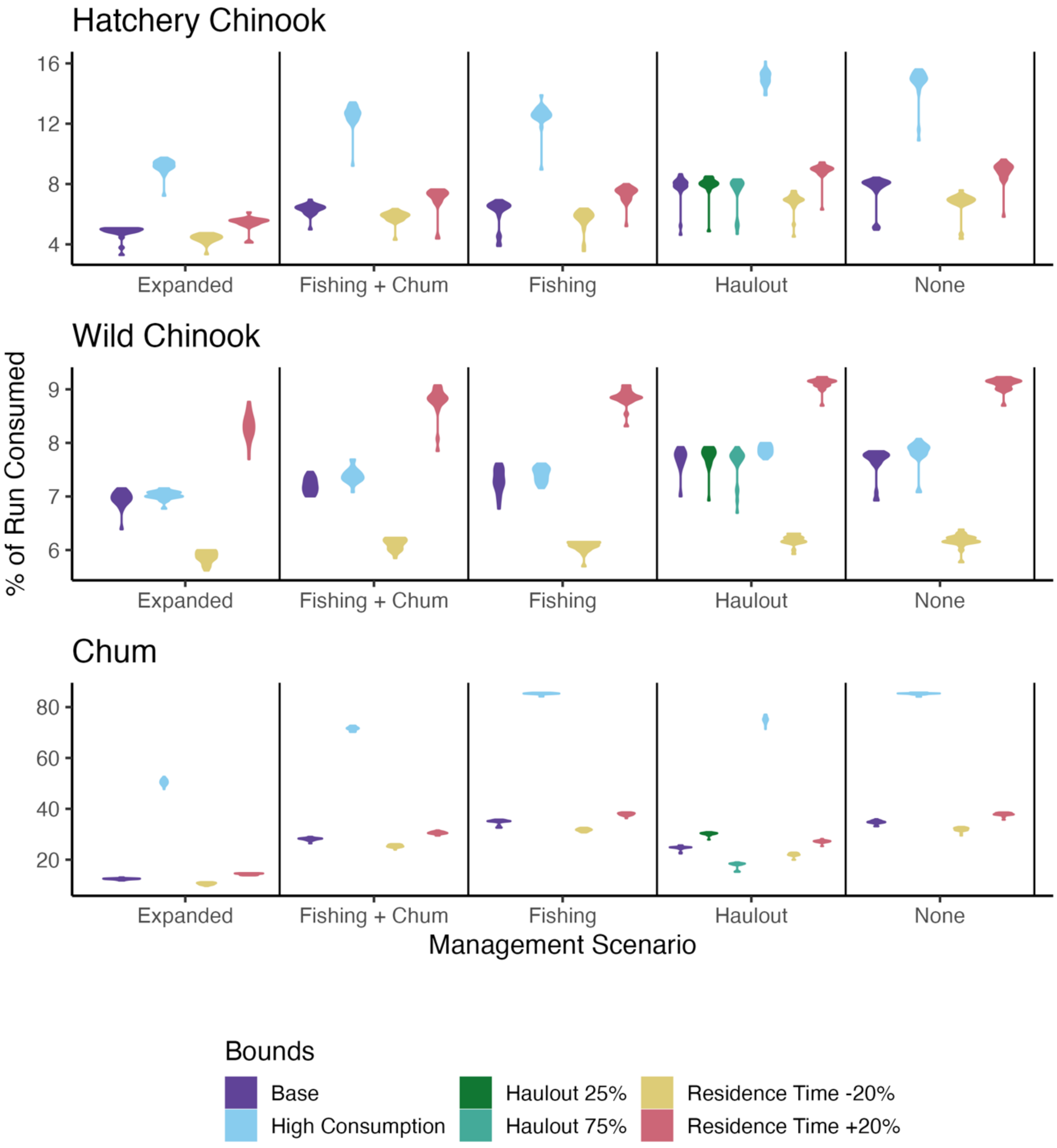

Figure 3.10: Management scenario parameterizations to probe key uncertainties in the Nisqually River case study model inputs. The Base parameterization is the low consumption parameterization. High Consumption is parameterized to represent gorging and other intense foraging behaviors. Haulout 25 and Haulout 75 refer to variations on the Haulout management scenario where we assume 25% or 75% population reductions. Residence high and low simulate 20% upper and lower bounds on residence time for each salmon run.

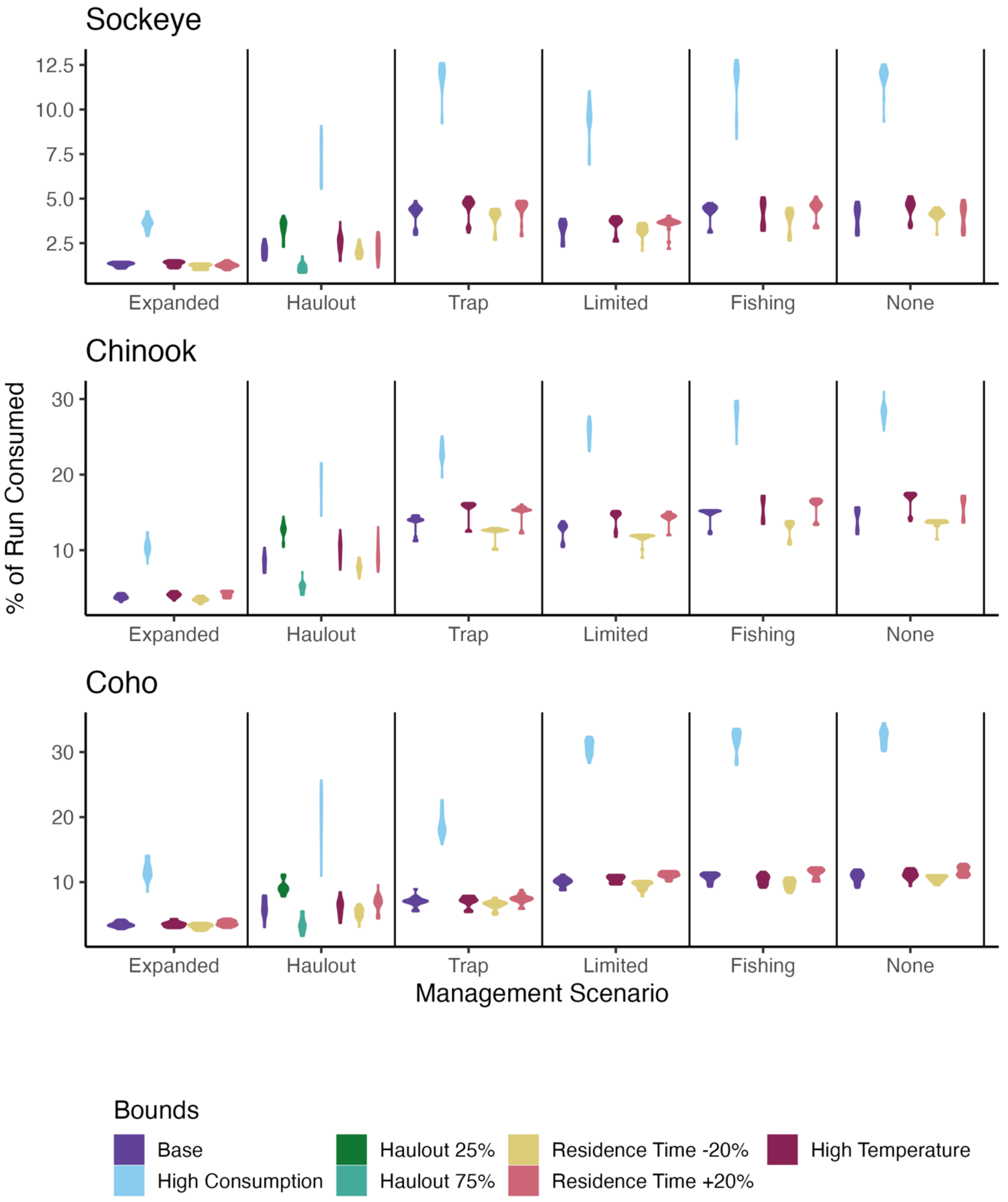

Figure 3.11: Management scenario parameterizations to probe key uncertainties in the Ballard Locks case study model inputs. The Base parameterization is the low consumption parameterization. High Consumption

is parameterized to represent gorging and other intense foraging behaviors. Haulout 25 and Haulout 75 refer to variations on the Haulout management scenario where we assume 25% or 75% population reductions. The Hot scenario explores the impact of elevated temperatures on residence times of salmon during the summer months. Residence high and low simulate 20% upper and lower bounds on residence time for each salmon run.

Discussion

Tribal pinniped harvest can be a viable tool to aid salmon when implemented with the intention of reducing encounters between pinniped predators and returning adult salmon. The question that often circulates in management meetings is whether pinniped management actions conducted on the limited spatial scale of tribal management could produce appreciable improvements in salmon survival large enough to justify the challenges of pursuing those actions via the complex legal pathways that govern them. We show here that management actions conducted on the scale of individual gauntlet systems, within tribal U&As, have the potential to increase salmon survival for some salmon runs, but the expected benefits are highly run-specific. Furthermore, the most effective strategy required a significant expansion in the amount of time that pinniped hunting occurred compared to current pinniped management authorizations.

The Expanded scenario, which simulated consistent lethal removal and harassment of pinnipeds during the entire timeframe when salmon were using the gauntlet, was the most effective pinniped management strategy in both gauntlets but required substantial effort. I explored the impact of the frequency of management activity in Chapter 2 and found that salmon survival declined as management frequency declined. The model presented in this manuscript provides managers with a platform to explore the tradeoffs between available management resources and salmon conservation objectives and the ability to design a management schedule that works best for the system they manage. I encourage practitioners to use this model in tandem with controlled experimental removals with well-designed monitoring to improve future management of these systems and the performance of the model (Washington State Academy of Sciences 2022). However, this kind of adaptive management would be most likely if management authority were delegated to tribal nations to manage pinnipeds in their U&As through one of three pathways: (1) an expansion of the interpretation of the fishing right of protecting gear and catch to also allow protecting the salmon run abundance from pinniped predators both during fishing and outside of fishing seasons; (2) a waiver of the take moratorium of the MMPA via Section 101 *et seq.* to open a directed pinniped harvest; or (3) through an amendment of the MMPA to recognize the right to hunt pinnipeds that tribes reserved in their treaties and exempt them from the limitations imposed by the MMPA (16 U.S.C. 1361 *et seq.*). These last two pathways to pinniped management provide tribes with the most flexibility to design programs that achieve salmon conservation objectives and operate within management resources. Recognizing that tribes have the right and the ability to appropriately manage pinnipeds in their U&As would benefit salmon recovery and respect the sovereignty of tribal nations (Clark 1985; Brand 2008).

In both case study gauntlets, some of the most feasible and impactful management scenarios rely on collaborations between agencies and/or tribal nations to accomplish notable improvements in salmon survival. In the Nisqually River, removing the barge haulout used by sea lions during the winter Chum salmon run could reduce interactions between sea lions and the diminishing winter Chum salmon population, but that action would require cooperation between the Tribe and the Billy Frank Jr National Wildlife Refuge at Nisqually, among other stakeholders and agencies in the area, to evaluate impacts to the submerged habitat and accomplish the removal if warranted. For the Muckleshoot Tribe, implementing management scenarios in the saltwater side of the Locks requires collaboration from the Army Corps of Engineers, Suquamish Indian Tribe, the Port of Seattle, and other agencies depending on the scenario (Mulvihill-Kuntz et al. 2024). It is likely that the Limited and Incidental scenarios would have been more effective if they had included lethal removals carried out by Suquamish fishers in their U&A. However, this additional benefit would still be very limited temporally by relatively short fishing seasons and the difficulty of carrying out lethal removals in close proximity to the Locks. In both instances of potential collaboration at the Nisqually River and at the Locks, evidence that such a collaborative undertaking would be beneficial will be helpful to securing interest and resources to accomplish the desired benefits for salmon.

To effectively implement management in gauntlet systems, we still require an adequate understanding of the relative impact of each pinniped predator species on individual salmon runs. In both case studies, the most effective management scenario for each run was the scenario that targeted the pinniped species with the largest predation impact on that run. For runs that are impacted by sea lions, reducing sea lion presence has a large impact on predation mortality due to their large per capita energetic needs. Managers also have more options for active management for sea lions than harbor seals, so there may be more pathways available to reduce the predation impact for those heavily impacted runs. Trapping and euthanasia is only effective for sea lions and has effectively reduced predation on salmonids by California sea lions in the Columbia River (Madson and Hevelingen 2017; Clark et al. 2021). Our results show that a similar strategy could be effective at improving the survival of Coho salmon at the Locks, and trapping efforts during the winter and spring could benefit outmigrating smolts as well. In the Nisqually River, the derelict barge haulout in the Billy Frank Jr National Wildlife Refuge is exclusively used by sea lions, and we found that removing it could lead to appreciable benefits for Chum salmon survival. While these scenarios might be effective options for the specific salmon runs impacted by sea lions, the variability in effectiveness of management actions between runs will require managers to potentially combine scenarios or prioritize scenarios that achieve conservation targets for specific salmon runs.

In our workshops many of the participants expressed concern about pinniped consumption of smolts in addition to returning adults. While we do not explore the use of this model to evaluate methods of reducing pinniped predation on out-migrating smolts, this would be an appropriate and useful implementation of this tool. At the Locks, the abundance of sea lions present in the area during the outmigration of smolts through the ship canal is much greater than the abundance present during the return of adults (Veirs et al. 2025), so evaluating scenarios that target reductions in interactions between sea lions and smolts, especially in the confined areas of the Ballard Locks, could be especially critical. In the Nisqually River, recent work quantified the impact of harbor seal predation on steelhead smolts and produced information that would prove useful in parameterizing a smolt gauntlet model in that system (Moore et al. 2024). Steelhead in the Nisqually River are listed as threatened under the Endangered Species Act, so acting to prevent mortality in a vulnerable life stage could have a critical impact on the longevity of their presence in the river. While the modeling results we present here were not intended to provide information about the impacts of pinniped management on smolt survival, management scenarios in both case studies that reduced pinniped abundance in the gauntlet during times when smolts from any salmon population would also be in the system could produce benefits for their survival. The challenge of modeling the conservation benefits of pinniped management for juvenile salmon survival is the uncertainty regarding the influence of additive or compensatory mortality dynamics through the rest of their life (Washington State Academy of Sciences 2022).

We did not include scenarios that explicitly explore the impacts of fisheries depredation by pinnipeds, even though this model structure could encompass those dynamics, because of a lack of data to inform parameter values. We know that depredation of fishery catch by marine mammals can have significant impacts on fishing livelihoods (Scordino 2010; Cosgrove et al. 2015; Glemarec et al. 2024), and participants in this project underscored the degree to which this issue impacts tribal fishers in their communities. We could manipulate the gauntlet model to account for depredation occurring on salmon that had already been captured by the fishery. To faithfully create this alternative model, we would need additional information about how depredation occurs in gauntlet systems, including the prevalence of depredation behaviors among pinniped populations and the efficiency of the fishery to estimate the availability of netted salmon on a given day. However, given appropriate inputs for the relevant dynamics, the gauntlet model could help explore the impact of fishery depredation on the exposure of pinnipeds to fear-inducing hunting activities and the spread of the deterrent effect of management through the pinniped populations.

Tagging data from the Ballard Locks tells a detailed story about salmon movement through the structure (Goetz and Quinn 2019). Some salmon, especially Chinook salmon, hold in the cool, deep freshwater at the eastern entrance to the large Locks and travel through the Locks back to the saltwater side multiple times while they adjust to the abrupt change in water temperature and salinity (Urgenson et al. 2021). There is uncertainty regarding residence times in the gauntlet, especially on the saltwater side, where observers record pinnipeds more frequently. Additional research specifically designed to explore fish movement through different areas of the gauntlet would greatly improve our understanding of their vulnerability to pinniped predators and also shed light on their movements while they navigate variable and challenging water conditions. This source of uncertainty is relevant because observation data tells us that the distribution and abundance of pinniped throughout different sections of the Locks is not uniform (Muckleshoot Indian Tribe, unpublished data), indicating that predation pressure may be more intense or less intense in specific areas of the Locks. Better data on pinniped movement through the Locks structures, and behavior of individual pinnipeds, would also provide helpful information to build a richer representation of the dynamics at the Locks and tighten our estimates of uncertainty due to salmon residence time.

In the Nisqually River case study, we did not include the full assemblage of salmon populations that spawn in the River. Coho salmon were not included, despite returning during the modeled timeframe, because project participants reported variability in their return timing and abundance and a lack of data to parameterize their presence in the gauntlet appropriately. This likely resulted in an underestimate of pinniped presence – specifically harbor seals – and predation mortality in the gauntlet during the end of the Chinook salmon runs and the beginning of the Chum salmon runs when Coho salmon would have been in the system. Since Chum salmon are much more heavily impacted by sea lion predation than harbor seal predation (Agha et al. 2021), we don’t anticipate that this underestimate would have had a significant impact on the effectiveness ranking of management scenarios, but the model would be improved if better data inputs to characterize this run were produced. We also did not include the Steelhead (*Oncorhynchus mykiss*) run in the case study due to the added complexity of incorporating kelting behavior, long freshwater residence, and bi-directional movement through the gauntlet (Nisqually Steelhead Recovery Team 2014). Steelhead begin to arrive at the Nisqually River in winter overlapping with the end of the Chum salmon run. Pinniped management that successfully reduced pinniped presence in the gauntlet during the Chum salmon run would likely also benefit Steelhead as they migrate through the gauntlet. We likely underestimate pinniped presence in the gauntlet during the end of the Chum salmon run because we do not incorporate the abundance of Steelhead also available to predators. We have information about the impact of pinnipeds on migrating adult steelhead in other systems, especially at the Ballard Locks, which could prove useful in parameterizing this additional population in future applications of this model (Cram et al. 2018). The parameterization of the case study without these two populations was sufficient to differentiate the effectiveness of very different categories of management scenarios, but more detailed fine-tuning of management options should be done with the full suite of adult salmon abundance in the gauntlet to better aid decision-making.

There are several sources of uncertainty in gauntlet systems that we can explore using this tool. As we demonstrated in this paper, the impact of environmental variability on salmon migration timing and the efficacy of pinniped management scenarios are easily parameterized and evaluated with this model, including the impacts of water temperature and flow regimes (Urgenson et al. 2021). We could also explore interannual variability in salmon abundance, such as that caused by pink salmon migration or otherwise abnormal year classes (Losee et al. 2019), in the context of the impact on management decisions. Figure 3.10 and Figure 3.11 illustrate the wide range of plausible pinniped consumption values for each run under different model parameterizations developed to capture the uncertainty in key data inputs for each case study. Substantial uncertainty in the contribution of salmon to pinniped diets in the region still exists (Washington State Academy of Sciences 2022), and individual diet variability adds to the difficulty of sampling populations effectively to achieve appropriate representations of average long-term foraging patterns (Nelson et al. 2021; Conwell et al. 2024). The upper and lower bounds on consumption that we explore in this paper represent the range of foraging behaviors, from salmon as a proportion of daily energetic intake to gorging and incomplete consumption. Future work could harness the agent-based model structure to more explicitly explore the uncertainty associated with individual diet specialization. While none of these alternate parameterizations resulted in a change in the ranking of management scenario effectiveness, they did impact the overall effectiveness of management at reducing pinniped predation and therefore might be relevant to management decisions in pursuit of specific escapement goals for individual salmon runs.

We could also explore the impact of variability in prey resources outside the gauntlet on pinniped decision-making with this tool. Diet studies on pinnipeds show that the majority of their diet is made up of non-salmonid prey (Lance et al. 2012; Tollit et al. 2015; Scordino et al. 2022), and it is reasonable to assume that the availability of these other prey items may impact their foraging decisions, though we still expect salmon to be preferred prey (Thomas et al. 2017). In this application of the model, we use a static value to represent the quality of salmon foraging opportunities outside the gauntlet to simulate pinniped decision-making processes. This could be expanded by the inclusion of a seasonally variable term that captures the presence of other temporally pulsed prey, such as herring (Siple and Francis 2016), that might alter the gauntlet foraging decision making process. Future work focused on summarizing the movement of non-salmonid pinniped prey items through Puget Sound and their subsequent availability to pinniped predators would help fine-tune this dynamic of the model.

We envision future applications of this model that consider the movement of pinnipeds between linked gauntlet systems. The model was constructed with the need to be adaptable to diverse gauntlet systems in Puget Sound and therefore could be parameterized for any other gauntlet system with the necessary data to inform the key inputs, mainly pinniped and salmon abundance and movement. One possible application of this would be to represent pinniped predation on salmon on spawning grounds, upriver of the gauntlet boundaries we use in this study, in the Nisqually River. Managers from the Nisqually Indian Tribe described significant impacts, both direct predation impacts and the behavioral impacts of disturbance during spawning, on salmon by sea lion predators traveling significant distances upriver (Craig Smith, personal communication 2025). They observe fewer individuals, and mostly sea lions, in those areas, but the impacts of disturbance by predators are potentially magnified during such an vulnerable stage in their life history (Bentley et al. 2014). This area could be characterized by a secondary gauntlet to capture this additional impact on salmon survival and reproductive success. The ability to use this framework to simulate the movement of pinnipeds, especially sea lions, between gauntlet systems as they follow the migration of returning salmon (Jefferson et al. 2023) could also provide a broader exploration of region-wide management scenarios that could be implemented collaboratively by tribal, state, and federal management agencies. While this would allow managers to understand the wider range of pinniped predation impacts in terminal areas, it still would not allow us to explore the impact of management on the magnitude of pinniped predation impacts in the open water areas of Puget Sound, which would likely be better explored without the use of computationally intensive agent-based tools. Previous studies have quantified pinniped predation impacts over large spatial and temporal scales in this region, and those tools would likely be better suited to evaluating the impacts of management at similarly broad scales in Puget Sound (Chasco et al. 2017; Nelson 2020).

The exercise of creating this model structure and gathering informative data inputs revealed data gaps in both case study systems, and in our understanding of pinniped predation dynamics more widely. Both case study systems would benefit from more research on pinniped movement and local distribution to better refine the results of the model. Specifically, work to individually identify and track pinnipeds as they access gauntlets and move throughout the region would allow us to understand the prevalence and spread of specialist behaviors, replacement of specialist individuals after removals, and movement of individuals between gauntlets. Past work in the Columbia River used California sea lion brands to track the spread of information about specialized foraging opportunities through social groups (Schakner et al. 2017b). Similar work could be achieved through the application of recently developed photo identification techniques for harbor seals (Birenbaum et al. 2022). This work would also benefit from a better understanding of salmon movement, specifically to inform the amount of time that fish spend in the gauntlet vulnerable to pinniped predation. At the Locks, acoustic tagging work was hugely helpful in providing estimates of salmon migration, holding, and recycling in different parts of the Locks complex that informed the vulnerability of fish to pinniped predators. Similar work in the Nisqually River and other candidate gauntlet systems would increase the precision of consumption estimates and improve our confidence in management scenario comparisons, though this model and our results are already relatively robust to different consumption parameterizations as explored above.

Fishery managers will use this tool to make more informed decisions to benefit salmon resources. One of our participants described that understanding the potential positive impacts of opening a fishery on reducing pinniped predation would help them weigh situations where they might otherwise have chosen to leave the fishery closed to conserve spawning abundance. We show that the presence of fishing activity where pinnipeds are also being lethally removed (the Fishing and Fishing + Chum scenarios) results in improvements in salmon survival by reducing pinniped presence and reducing predation mortality. Being able to access this tool allows them to understand the tradeoffs between fishery mortality and predation mortality and make a more informed decision that is right for their fishing community and ecosystem. Another participant described that this work enabled them to reframe fishing effort as a conservation tool, especially in the context of potential Endangered Species Act listings that would prevent managers from opening fisheries even to manage the presence of pinnipeds. Participants also expressed interest in the ability to use the tool to understand how much they might need to invest in management programs to achieve a desired improvement in escapement. Each of these uses speaks to the powerful vision of tribal fishery managers in the region who are able and interested in using the tools at their disposal to improve outcomes for salmon and preserve the fishing traditions of their communities.

Tribes have been at the forefront of ecosystem-based fisheries management since time immemorial and have a strong track record of using every tool at their disposal to protect the ecosystems they steward. This includes putting their treaty rights on the line in court to preserve their fishing rights, protect salmon habitat, and prevent exploitation by Western management regimes. This tool provides evidence that tribal pinniped harvest practices could play an important role in the management of salmon futures in Washington.

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Appendix

Appendix 1: Participatory Workshop Summaries

A full list of workshop participants is available in Appendix 2.

Scoping Workshop – Tribal Pinniped Hunting

This initial workshop occurred in August of 2022 and specifically invited tribes to discuss their interest in a research project focused on pinniped management, their histories with pinniped management, and their capacities to conduct pinniped management activities with existing resources and structures.

Workshop One – Information Gathering

This first participant workshop occurred in January of 2023 and was focused on identifying key research priorities that could be addressed through this project and turning those into project objectives. Three key themes emerged from the first participant workshop. The first was concern about the outsize impact of “specialist” animals and the transmission of that behavior to naïve individuals. Participants also described the variation between systems in terms of salmon species and runs, pinniped species and timing, geography and human-built structures that influence salmon vulnerability and pinnipeds access to salmon, and the harvest landscape determined by U&A boundaries. Lastly, participants emphasized the importance of monitoring before, during, and after any potential removal programs to address identified data gaps. As a group, the participants decided that some of their key questions might be best addressed by focusing on case studies of a couple very different systems. The goal would be to develop models that could be adapted to represent the unique attributes of different systems and could be used to answer some of these questions about specialist behaviors, responses to removals, and the efficacy of different harvest structures. The lessons learned from those case studies would then be used to answer questions about the impact of pinnipeds on salmon in the wider Puget Sound and how harvest might be able to mitigate that impact. The group agreed that the Muckleshoot and Nisqually Tribes had the most personnel capacity and existing monitoring in their systems to be good case studies, so the Hiram M. Chittenden Locks (Ballard Locks) and Nisqually River were identified as starting points.

Technical Advisory Group Meeting

The Technical Advisory Group received a presentation on the structure of the model in June 2024. The group discussion focused on aspects of the system that were not captured, or not captured in adequate detail in the model, and whether those limitations should be remedied during this project or in future work. The conversation spanned non-lethal predation impacts including stress and injury, pinniped gorging behaviors during foraging, habitat use by salmon and pinnipeds, pinniped specialist behaviors, and details of how we capture bioenergetic components of the model. All this feedback helped identify weaknesses in the model at that point, additional model components to include, data inputs we hadn't incorporated, and additional applications of the model.

Workshop 2 – Model Refinement

The second participant workshop occurred in November 2024 and focused on presenting the model structure and discussing preliminary results from case study models. I introduced the gauntlet model structure and the main objectives that it was built to address: 1) Create a tool that can help us compare returning adult salmon survival under different pinniped management scenarios; 2) Make sure that the tool is flexible enough to honor the diversity of salmon systems in Puget Sound and can be parameterized to simulate those different systems; 3) The tool should enable us to explore the pinniped behavioral response to management and foraging opportunities in order to identify effective interventions that address "salmon specialist" behaviors; and 4) Use the tool to identify data gaps for further research and to help structure monitoring programs.

The discussion during this workshop centered around ensuring that the gauntlet model incorporated the dynamics that participants observe in their systems. We discussed specific parameter values for aspects of salmon and pinniped abundance, seasonality, and movement. The group also identified multiple strange aspects of model behavior that needed addressing, specifically: replacement of pinnipeds into the system after removals was almost instantaneous which was not realistic, and all pinnipeds in the source pool should not attend the gauntlet because some individuals might specialize on prey that is predominantly present outside the gauntlet. The group also identified multiple areas where parameter inputs could be better informed using existing data, especially to fine-tune species-specific consumption behavior and bioenergetics.

The group discussions identified a couple of opportunities for data-sharing between participants to better inform salmon movement via catch data, pinniped movement via tag data, and pinniped behavior via observational studies from other systems in the region. A few other sites in the region that would be good candidates for future gauntlet models were identified during discussions, and the need to keep taking steps to address pinniped predation impacts across the region was reiterated.

Workshop 3 – Presentation and Discussion of Results

This third and final participant workshop in May 2025 focused on presenting modeling outcomes and discussing their utility for the managers in attendance. The group generally agreed that the structure we developed and tested with the two case studies addressed the objectives identified in the previous workshops and could prove useful to inform management and to answer other research questions. The main management application was providing support for the concept of tribal fisheries as a management tool that could be useful for managing pinniped populations and therefore protecting salmon from predation mortality. We discussed other applications of the model, including to explore predation impacts on out-migrating juvenile salmon in gauntlets, evaluate management options in other gauntlet systems in the region, understand the potential impacts of depredation on management effectiveness, and exploring other axes of environmental or interannual variability in gauntlet dynamics (e.g. pink salmon years, temperature fluctuations, salmon abundance variability).

Appendix 2: Full Participant List

Appendix 2: Full participant list showing names, affiliations, and number of workshops they attended during the project process (5 total). Participant affiliations refer to their affiliation at the time of the workshop, and participants whose affiliations changed during the project are listed separately under both affiliations. Names with an asterisk indicate members of the PI Team, ^{T} indicates involvement in the Technical Advisory Group, and ^{C} indicates that they had a critical role in case study development in addition to their workshop participation. Those who contributed to the project but did not attend workshops are listed in the acknowledgements.

Name	Affiliation	Workshops Attended
Jonathan Scordino*	Makah Tribe	5
Rob Jones*	Northwest Indian Fisheries Commission	5
Tim Essington*	University of Washington	5
Ava Fuller^C	Muckleshoot Indian Tribe	4
Casey Clark^T	Washington Department of Fish and Wildlife	4
Casey Ruff^T	Swinomish Indian Tribal Community	4
Craig Smith^C	Nisqually Indian Tribe	4
Mark Nelson	Lummi Nation	4
Megan Moore^T	National Marine Fisheries Service	4
Andrew Berdahl*	University of Washington	3
Chris Ellings^C	Nisqually Indian Tribe	3
Dylan Bergman	Point No Point Treaty Council	3
Emily Wirtz	Lummi Nation	3
Gary Morishima	Quinault Indian Nation	3
Mike Mahovlich^C	Muckleshoot Indian Tribe	3
Todd LaClair^C	Muckleshoot Indian Tribe	3
Zoë Lewis	Lummi Nation	3

Brian Hoffman	Hoh Tribe	2
Isaac Kaplan[T]	National Marine Fisheries Service	2
Jason Schaffler[C]	Muckleshoot Indian Tribe	2
Jed Moore[C]	Nisqually Indian Tribe	2
Joe Scordino	National Marine Fisheries Service (Retired)	2
Joseph Peters	Squaxin Island Tribe	2
Kirsten Vacura	Muckleshoot Indian Tribe	2
Leah Mellinger	Port Gamble S'Klallam Tribe	2
Lolinthea Hinkley	Lower Elwha Klallam Tribe	2
Oliver Miler	Northwest Indian Fisheries Commission	2
Robert Roose	Stillaguamish Tribe of Indians	2
Ryan Walsh	Makah Tribe	2
Sophia Rice	Lummi Nation	2
Adrian Purser	Port Gamble S'Klallam Tribe	1
Bernard Afterbuffalo	Hoh Tribe	1
Cassandra Sullivan	Port Gamble S'Klallam Tribe	1
Chris Madsen	Northwest Indian Fisheries Commission	1
Cleve Jackson	Quinault Indian Nation	1
David Troutt[C]	Nisqually Indian Tribe	1
Diego Holmgren	Tulalip Tribes	1
Ed Johnstone	Quinault Indian Nation	1
Eric Ward[T]	National Marine Fisheries Service	1
Gary Tatro Jr	Stillaguamish Tribe of Indians	1
George Jones	Port Gamble S'Klallam Tribe	1
Jacob Rodrigues	Muckleshoot Indian Tribe	1
Jasper McCutcheon	Makah Tribe	1

Jenny Stern	National Marine Fisheries Service	1
Jillian Howard	Muckleshoot Indian Tribe	1
John Bryson Jr	Quinault Indian Nation	1
Kadi Bizyayeva	Stillaguamish Tribe of Indians	1
Leo LaClair	Muckleshoot Indian Tribe	1
Maia Bellon	Nisqually Indian Tribe	1
Matthew Ives	Port Gamble S'Klallam Tribe	1
Megan Hintz	Port Gamble S'Klallam Tribe	1
Michael Grant	Sauk-Suiattle Indian Tribe	1
Michael Sevigny	Tulalip Tribes	1
Nora Hickey	Northwest Indian Fisheries Commission	1
Patrick Braese	Squaxin Island Tribe	1
Ron Charles	Port Gamble S'Klallam Tribe	1
Russ Hepfer	Lower Elwha Klallam Tribe	1
Samantha Rae	Lower Elwha Klallam Tribe	1
Samantha Rae	Suquamish Tribe	1
Shawn Yanity	Stillaguamish Tribe of Indians	1
Tara Strachan	Lummi Nation	1
Violet Rideout	Lummi Nation	1
Zachary Schakner^{T}	National Marine Fisheries Service	1