

# **Rethinking quantitative fisheries: a case study of a values-driven approach on the K'vaí (Koeye)- Hísn̓ (Sockeye) Haílzaqv (Heiltsuk) fishery**

**by**  
**Sara Tremblay-Boyer**

Bachelor of Science, University of British Columbia, 2017

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## Declaration of Committee

**Name:** Sara Tremblay-Boyer

**Degree:** Master of Resource and Environmental Management

**Title:** Rethinking quantitative fisheries: a case study of a values-driven approach on the Kvaí (Koeeye)-Hísq (Sockeye) Hailzaqv (Heiltsuk) fishery

**Committee:**

**Chair: Laura Tate**  
Lecturer, Resource and Environmental Management

**Jonathan Moore**  
Supervisor  
Professor, Biological Science and Resource and Environmental Management

**William Atlas**  
Committee Member  
Adjunct Professor, Biological Sciences

**Anne K. Salomon**  
Committee Member  
Professor, Resource and Environmental Management

**Emma Hodgson**  
Examiner  
Adjunct Professor, Resource and Environmental Management

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## Abstract

Due to the Indigenous resurgence and decolonization movements seen across North America in recent decades, it is now well-documented that resource management has a deeply colonial and capitalist history (Berkes & Fikret, 2003; A. J. Reid et al., 2021) that still influences how science is conducted. In this political context of indigenizing environmental management model, we asked ourselves how we could rethink the quantitative fisheries management process to make space for multiple perspectives within a complex fisheries system. Here, we co-developed a value-driven forward simulation centred on Haítzaqv values, knowledges and practices to explore trade-offs amongst alternative harvest strategies for the food, social and ceremonial fisheries of hísn̓ in Kvaí River system. Three key findings emerged from our closed-loop simulation. First, we found clear evidence that an in-season harvest strategy can mitigate some climate risks on the long-term resilience of the Kvai system hísn̓ population. Second, a weighted trade-off analysis can decrease mismatches between contemporary fishing management and local communities. Third, local monitoring methods allowed for more effective, nuanced quantitative advice for management. Finally, we discuss insights learned using a participatory modelling process. Our research demonstrates how a values-driven approach in quantitative fisheries can be a practical way to create space for multiple ways of knowing that could support climate-resilient and socially just human-salmon relationships.

**Keywords:** Indigenous-led governance; fisheries; co-production; resource management; population modeling; salmon; values

*"We have been taught water is a living thing and that we have a responsibility to keep our waters safe. Our Elders tell us that if our waters are healthy our community is healthy - physically, mentally, spiritually and culturally."*

*- Heiltsuk Tribal Council, 2018*

*To Kvaí, a river that takes and gives, but especially teaches.*

*À mes neveux; Ysaac, Ethan, Zackary, et Anthony...*

*L'amour est partout où vous allez.*

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## List of Acronyms

BH	Beverton-Holt
HIRMD	Heiltsuk Integrated Management Department
MAC	Maximum Allowable Catch
MSY	Maximum Sustainable Yield
SES	Socioecological system
TC	Total Catch

## Key terminology and symbols

Constant abundance harvest strategy	A harvest strategy that holds the population at a set abundance target ( $S_{\text{target}}$ ) by harvesting the difference between the annual forecasted run and $S_{\text{target}}$ .
Constant catch harvest strategy	A harvest strategy that allows the same total catch (TC) to be annually harvested, regardless of the annual forecasted run
$F_{\text{msy}}$	Fishing mortality producing the maximum sustainable yield (MSY)
$H_w$	Harvested number of fish in. a given year $w$ , used in the in-season fishing threshold strategy
$H_y$	Harvested number of fish in a given year $y$
In-season fishing threshold harvest strategy	A harvest strategy that allows harvest only if the forecasted run reach a specified size threshold ( $S_{\text{fishing}}$ ), the harvest decision is updated every week
Maximum Allowable Catch (MAC)	Maximum number of fish that can be removed from the sockeye population within a year, used in the in-season harvest strategy
MSY	Maximum sustainable yield
Overfished population	An overfished population has a population at time $y$ that has a lower abundance than $S_{\text{msy}}$
Overfishing	Overfishing happens when fishing mortality is higher than $F_{\text{msy}}$
$S_{\text{abundance}}$	Population abundance objective for the Koeys sockeye population.
$S_{\text{fishing}}$	Spawner abundance fishing threshold below which fishing is prohibited, used in the in-season fishing threshold harvest
$S_{\text{gen}}$	Probability of recovery to $S_{\text{msy}}$ within one generation in the absence of fishing given existing environmental conditions
$S_{\text{msy}}$	Spawner abundance at maximum sustainable yield
$S_{\text{target}}$	Abundance target for the spawner population used in the constant abundance harvest strategy
Total Catch (TC)	The number of fish to be removed from the sockeye population in a given time period, used in the constant catch harvest strategy

## Self-location and positionality statement

“Owning one’s subjectivity in research is critical in decolonizing research, especially for Western academically trained scholars who tend to privilege Western-produced knowledge over Indigenous knowledges. “

Mcgregor, et al. 2018

I came across this quote when reading a paper from Reid, *et al* (2020), and I thought it expressed so eloquently the importance of a positionality statement, especially as a Western “scholar”. And while I still have doubts about my eligibility to call myself a scholar, I highly recommend reading this paper. To honour my Heiltsuk friends’ talent for storytelling, here’s the short story of who I am in relation to this, my research work.

I was raised in a separatist house, with Radio-Canada playing in the background and my parents loudly singing the Québécois national anthem every Saint- Jean-Baptiste holiday. They taught me to be a proud Québécois; to love our music, our folklore, and our liberal policies which gave us free health care and schooling. Talking and criticizing politics is just part of our culture, so it is not surprising that my first memory of what it meant to be Québécois was the day of the referendum in 1995. I don’t remember much, just my dad saying, “tomorrow, hopefully, we will be our own country.”. I was 5 years old, and honestly, that was mostly confusing. I probably didn’t even know what “country” meant at that time. However, it left me with the feeling of “us” against “them”, which is deeply embedded within Québec’s identity. “Them” often referred to: the Anglos, Canada, Jean Chrétien, everyone else who is not white and Québécois.

It’s only when I moved to BC that I started to realize that us, Québécois, were colonizers too. Since then, I have been thinking a lot about our responsibilities towards Indigenous people, but also immigrants, and how we fail them most of the time. Shouldn’t we be the first ones to step in and advocate for many different cultures and languages since we fought for so many decades to preserve our culture and language against a sea of Anglos?

This understanding of my positionality changed further when I worked in the Downtown-East side as a front-line worker between fieldwork seasons. I became acutely aware of the privileges I hold as a white, middle-class cis-woman, but also as someone who had access to counsellors, doctors that believed in my health issues, and access to

safe housing. I came to understand then that a privilege can simply take the form of having access to a warm bath at the end of a tough day.

I learned (or unlearned) further when I started grad school; I became aware that I also have responsibilities as a non-indigenous researcher working on Indigenous lands. I didn't arrive at this realization by myself. I had generous friends, teachers, and particularly educating books. One book in particular changed how I perceive science and taught me the importance of learning about my colonial perceptions and how normalizing Western knowledge can in some cases cause harm (Kovach, 2009). I learned that I still have much more to unlearn, and this education process is a life long journey.

## **Guiding values for a respectful research approach; Responsibility, Reciprocity, and Relevance**

I took a class called: “Pulling Together: A Guide for Researchers, *Hitk’ala*”, and that is when I realized the importance of having guiding values for a respectful research approach. I learned that caring and having good intentions are essential, but it is not often sufficient. Within academia, it is easy to lose sight of what is truly important; actions always have a higher impact than intentions. Doing research in a good way is not a perfect process; it takes constant work. So, conducting research informed by guiding values is a way to keep myself, and my non-indigenous collaborators, accountable to the community for the research we try to do.

### **Responsibility;**

I try to lead with the heart. It entails pausing for a minute and letting myself feel uncomfortable truths. It means feeling the heaviness and the sadness of what has been lost, like when the grandfather of my friend tells me that back in his days, there were herrings and abalones right there, all around Waglisla (Bella Bella). That his pain is still present, it’s not some abstraction of history. The atrocities and injustices that happened to Indigenous communities are not only in the past but are still continuing today. Mourning with and for my Indigenous friends and their communities is important because with mourning, comes anger, a powerful fuel to keep fighting against injustices. It reminds me of the importance of never being complacent with the system as it is today, even when it would be so much easier to go with the business-as-usual models. It ties me back to my responsibility as a settler and a biologist: collectively and individually, we must do better, even if it happens one small project at a time.

### **Reciprocity;**

My conception of what reciprocity means has evolved drastically throughout my graduate degree. This process has taught me that to uphold Heiltsuk values, I should strive for respectful and reciprocal relationships with all the humans and nonhumans of Heiltsuk territory. But... What does it mean to give back to the land and the fish as a non-indigenous researcher, and how am I supposed to reciprocate to them meaningfully?

What does it mean for a settler to practice reciprocity with the nation you collaborated with and the friends you made along the way? My friend Kai made me a sandwich with canned salmon when he learned I had never tasted it before. He and his sister, Clea, brought me to Huyat and told me stories about wolf and p'kvs (sasquatch). They patiently repeated the Heiltsuk word every time I asked. I am still unsure how best I can show them the same generosity and care their family shows me, but I know it starts with trying my best to make space within my research for the inspiring culture, practices, and values I learned from them.

### **Relevance;**

Who I am and the way I see the world shapes how I relate to the land and conduct my research. Thus, what I perceive as relevant is directly connected to my values and assumptions. Ensuring that the research serves the community above my own agenda is critical. I try to practice humility and I try to recognize the needs of the community over my own expectations through constant self-reflection. I try to learn and to listen instead of speaking. I know I have made mistakes and will continue to do so, so I take responsibility for them and carry on.

# 1. Introduction

With the continued failure of state-led management agencies in halting environmental devastation, (Artelle *et al.*, 2021; IPCC, 2023), there are increased calls to transform natural resource management systems towards adaptive and place-based governance systems (Berkes, 2003; Salomon *et al.*, 2019). In a place-based governance systems, the decision-making processes are guided by the social norms and cultural values shared by the local community (Balvanera *et al.*, 2017; Armitage *et al.*, 2019; Beveridge *et al.*, 2020). Local knowledge strengthens environmental stewardship and governance practices by improving the understanding of socioecological system (SES) dynamics (Folke *et al.*, 2005). Key SES properties such as functional redundancy and response diversity are critical for maintaining the resilience of SES, which is defined as the capacity of an ecosystem to adapt and persist through changes, whilst still supporting human well-being (Biggs *et al.*, 2012). Management practices, informed by local knowledges, often enhance adaptation through collective learning and sharing successful practices to buffer disturbances (Smit and Wandel, 2006; Armitage, Marschke and Plummer, 2008; Whitney *et al.*, 2017). As a result, place-based adaptive management practices are a promising approach to deal with ecosystem complexity, as they often lead to better social and ecological outcomes (Schultz *et al.*, 2015; Lee *et al.*, 2019; Burt *et al.*, 2020).

Place-based governance and environmental stewardship are not new ideas; Indigenous peoples worldwide have been applying these management principles for millennia (Trosper, 2003; Lee *et al.*, 2019; Atlas *et al.*, 2020; Artelle *et al.*, 2021; Reid *et al.*, 2021). Indigenous stewardship usually fosters human-ecosystem relationships centered on respect and reciprocity (Haggan *et al.*, 2004; Brown and Brown, 2009; Côté, 2019). Typically, these relational-reciprocity approaches are grounded in the belief that the health and well-being of a society are strongly tied to the health of the land and waters (Newell and Ommer, 1999; Turner *et al.*, 2013; Turner, 2020). Indeed, many Indigenous societies believe in a “kincentric ecology”: nature and humans are a part of one extended ecological family (Salmon, 2000). As such, taking care of the land is a responsibility that is not limited solely to being a resource user (which in and of itself is a colonial framing), but that also encompasses reciprocal obligations to other-than-human species and their environments (Salomon *et al.*, 2023). Upholding these obligations

supports the resilience of socioecological systems (Heiltsuk Tribal Council, 2018), and thus, many place-based Indigenous governance systems are leading examples in fostering more effective and socially just environmental stewardship (Kimmerer and Lake, 2001; Lee *et al.*, 2019).

Using a place-based governance system, Indigenous people from the Pacific Northwest successfully managed salmon fisheries for millennia before colonization (Trosper, 2003; Haggan *et al.*, 2004; Turner, 2020). Indigenous management systems from this region were reliant on the highly productive but variable marine ecosystem, with high abundance of salmon happening only at certain times of the year in specific locations (Turner *et al.*, 2013). As a result, these periodic variations in resource abundance required specialized fishing techniques which shaped how coastal Indigenous fishing practices were developed (Atlas *et al.*, 2020). For instance, selective fishing techniques allowed non-target species to be released, whereas fish with the desired characteristics, such as male, or weakened fish, would be harvested (Brown and Brown, 2009; Turner, 2020; Morin *et al.*, 2021). While we can only estimate salmon harvest numbers from the pre-colonial era, they are thought to be at least comparable to the industrial harvests of the early twentieth century (Newell, 1993; Menzies and Butler, 2007). To maintain harvest levels over time without depleting salmon populations, required knowledge on how to carefully enhance, monitor and use salmon resources was passed down through generations, resulting in a wealth of intergenerational teachings and practices on how to responsibly steward salmon populations. (Campbell and Butler, 2010; Housty *et al.*, 2014; Artelle *et al.*, 2019; Reid *et al.*, 2021).

With the colonization of British Columbia by European settlers, salmon fishery management changed drastically; it went from a “relational- reciprocity” approach to a market-based economic approach (Harris, 2017; Silver *et al.*, 2022). Colonial fisheries have prioritized extracting salmon populations for short-term profit (Lepofsky and Caldwell, 2013; Salomon *et al.*, 2019; Atlas *et al.*, 2020; Reid *et al.*, 2021). This imposed Eurocentric value system led to different fishing methodologies and management systems; the fisheries moved from communal, in-river, terminal fisheries to the open ocean mixed-stock harvest, with centralized, large-scale governance systems (Atlas *et al.*, 2017, 2020). Furthermore, this top-down regulatory process created a lack of incentive to conserve fish populations among commercial fishers and stakeholder groups, as they were not directly accountable for the impacts of their management

policies (Newell, 1993; Harris, 2017). Additionally, the B.C.federal government outlawed Indigenous fishery technologies in the late 19<sup>th</sup> century and excluded Indigenous people from the policy-making process (Higgs, 1982; Harris, 2017; Silver *et al.*, 2022). These colonial injustices drastically reduced the capability of Indigenous communities to access salmon resources, while undermining Indigenous stewardships, traditional practices, and ways of life (Frid *et al.*, 2023).

In the face of climate change, resilient salmon socioecological systems are more necessary than ever. However, adapting fisheries management systems to foster resilient salmon populations is an ongoing challenge (Schindler *et al.*, 2008). Indeed, environmental disturbances driven by climate change are hard to predict, (Holsman *et al.*, 2019; B. Connors *et al.*, 2020; B. M. Connors *et al.*, 2020) and since Pacific salmon productivity is linked to ocean conditions, ongoing climate change and predicted warming of the ocean could impact the productivity of salmon populations (Mueter, Peterman and Pyper, 2002). Consequently, if fisheries practices are not adjusted to account for scientific uncertainties and rapidly changing environments, they could further increase the risk of overfishing and depleted populations (Moore, Connors and Hodgson, 2021). There is an urgent need for fisheries management to integrate mechanisms that inherently foster resilience towards unpredictable climate variability.

To promote the ecosystem's potential adaption to climate change, fisheries science is increasingly moving away from single-species stock assessment to ecosystem approaches that can assess the impact of uncertainties for achieving management goals (Fulton *et al.*, 2014; Geary *et al.*, 2020; Link *et al.*, 2020). For instance, integrated management strategy evaluations are now generally considered to be the most appropriate fisheries assessment approach as they can account for key uncertainties that influence fish population dynamics (Punt *et al.*, 2016; Goethel *et al.*, 2019). These analytical procedures usually use simulation models of a fisheries system to explicitly compare trade-offs between the stated management objectives, and to quantify how robust management practices will be across a range of unknown future ecosystem states (Rademeyer *et al.*, 2007). Yet, these approaches often focus solely on commercial fisheries (Richerson, Levin and Mangel, 2010; Marshall *et al.*, 2018), without involving the rights holders, cultural harvesters and local communities who directly depend on these fisheries (Adams *et al.*, 2021). Hence, limiting mismatches between fisheries science analysis and community goals is one of the foremost challenges in

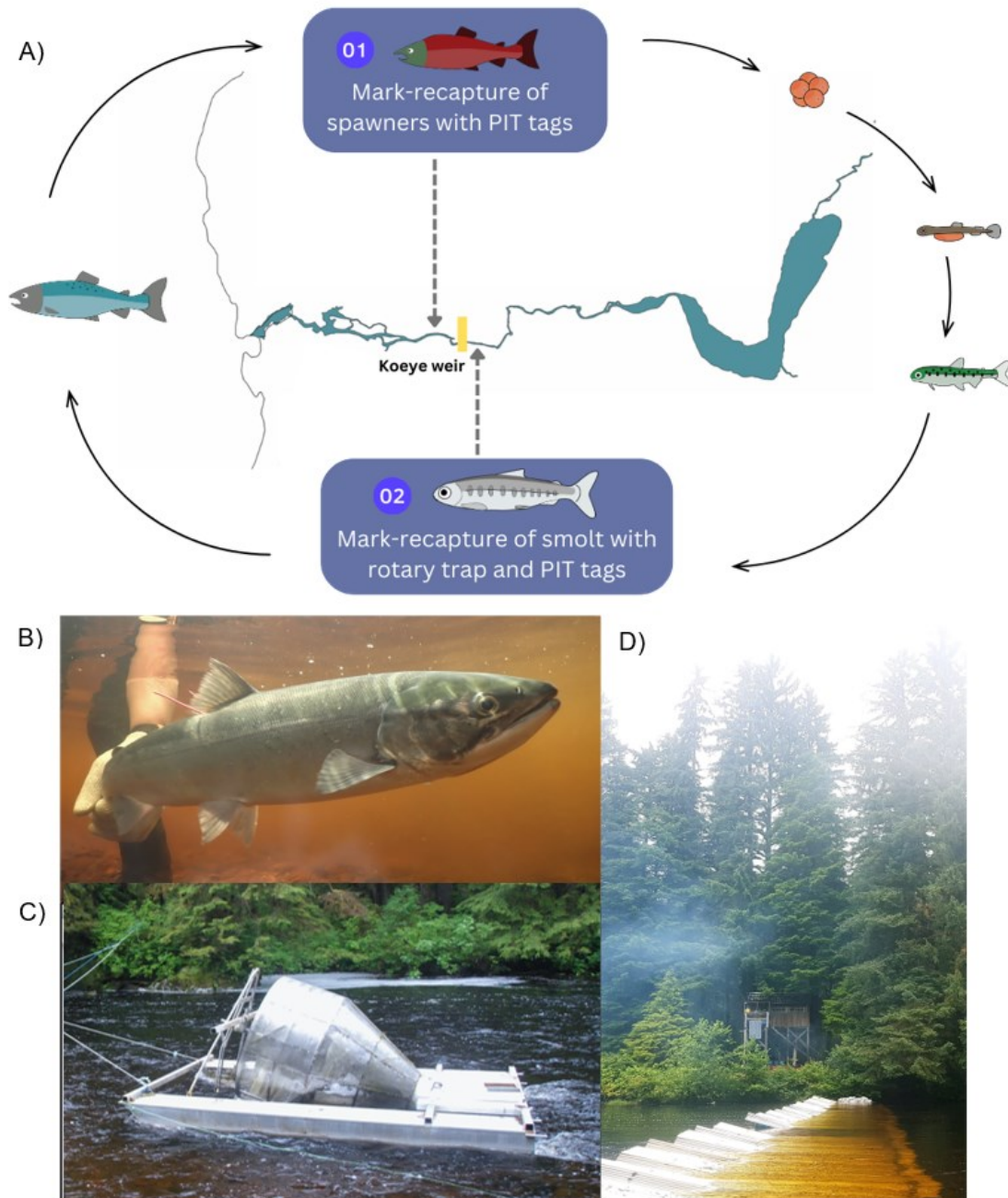
fisheries management (Cinner *et al.*, 2020; Cooke *et al.*, 2021; Connors, 2023). This reality creates a pressing need for fisheries management to transition towards a more holistic place-based approach (George and Reed, 2015; Balvanera *et al.*, 2017), one that can integrate key ecosystem uncertainties as well as upholding the values, knowledge systems and cultural practices of the local communities.

For a socially just place-based governance, Indigenous communities must be included in the governance and management of fisheries (Wolf, Alice and Bell, 2013; Reid *et al.*, 2014). For this reason, many Indigenous and non-Indigenous leaders are pushing for a decolonized management approach (Tallbear, 2014; Salomon *et al.*, 2018; Artelle *et al.*, 2021; Silver *et al.*, 2022). Such an approach emphasizes the importance of honoring local stewardship protocols and acknowledges Indigenous rights and responsibilities to manage their resources (Housty *et al.*, 2014). Notably, to help guide this transformation in management systems, recent studies have identified key avenues for challenging dominant colonial approaches in fisheries science. For instance, recognizing Indigenous worldviews as valid research methodologies can help create a polycentric governance that upholds traditional values and practices (Burt *et al.*, 2020). Furthermore, management policies should be informed by a plurality of perspectives and knowledges as well as centering research protocols and interpretations around local values and worldviews (Latulippe and Klenk, 2020). In addition, cultural relationships between humans and non-humans should be reflected in management protocols to transition from management systems that focus exclusively on extraction (Adams *et al.*, 2023). In summary, a decolonial (or Indigenized) approach to fisheries is necessary to support Indigenous communities in reclaiming their connection to their land and their inherent rights to managing their natural resources (Belcourt, Swaney and Kelley, 2015).

To co-develop alternative management approaches that support climate resilient and socially just human-salmon relationships, we collaborated with Haítzaqv Nation, to ask; 1) what worldviews, governance principles, values, and management objectives should inform future food, social and ceremonial fisheries of hísñ in the Kvaí River system? 2) What fishing thresholds and harvest management strategies will allow the Haítzaqv Nation to meet their objectives amid swiftly changing climate conditions? This project was a collaboration among myself, Kyle Wilson, Will Atlas, Jonathan Moore, William Housty, and Mike Reid. Accordingly, while I, Sara T-B take full responsibility for leading this project, throughout this thesis I use "we" to refer to this collaborative work.

## 2. Methods

### 2.1. Study system



**Figure 1. Kvaí Salmon Ecosystem Study**

A) Map of the Kvaí watershed with the hísñ life-cycle and the mark-recapture monitoring projects. B) A tagged hísñ for the adult mark recapture project. C) The rotary trap used to capture smolt for the smolt mark-recapture project. D) The weir on the Kvaí river. Salmon drawings made by Samantha Wilson, and they are used with permission of the artist.

### **2.1.1. Haítzaqv (Heiltsuk)- salmon relationship**

The connection of the Haítzaqv (Heiltsuk) people to the salmon is intricate; salmon are kin. Thus, they are not solely seen as a food resource, but rather as ancestral gifts (Heiltsuk Tribal Council, 2018 ). The responsibility to take care of the salmon and to have reciprocal respect has always been at the core of the Haítzaqv-salmon relationship. The foundation of this relationship is embedded within the Ğvılás, the laws of Haítzaqv ancestors (Brown and Brown, 2009). Those ancestral laws guide the social, cultural, and spiritual norms of how to interact with the land and the waters Haítzaqv people live on. For instance, responsibility (Sála), a guiding principle of the Ğvılás, defines the obligation for the Haítzaqv people to practise responsible stewardship to the salmon and their environments. Since Haítzaqv always have relied heavily on salmon for subsistence and livelihoods (White, 2006; Housty *et al.*, 2014), harvesting salmon in a good way upholds the Ğvılás, and honours the kinship ties between the Haítzaqv and the salmon (Brown, 2022).

### **2.1.2. K'vaí (Koeye)- hísn̓ (sockeye) driven ecosystem**

K'vaí is a remote salmon-bearing river on what is now known as the Central Coast of British Columbia. The K'vaí watershed is part of a unique and globally rare ecosystem, the coastal temperate rainforest. Due to abundant precipitation and a temperate climate, the landscape is mainly dominated by large coniferous trees, with mosses, lichens, and fungi (Price *et al.*, 2009). In addition, K'vaí watershed is one of the few coastal watersheds in British Columbia that the logging industry has spared. As a result, the valley is almost entirely roadless and contains some of the oldest old-growth forests in the Pacific Northwest region (Housty *et al.*, 2014). The watershed consists of two lakes, K'vaí Lake and Upper K'vaí Lake; however, only K'vaí Lake is home to a population of hísn̓. Juvenile hísn̓ rear in the K'vaí Lake for one to two years prior to their downstream migration. After spending two or three winters at sea, they start their upriver spawning migration from June to August, a period of high resource abundance that drives bears and eagles to congregate around the K'vaí River (Atlas *et al.*, 2021). This marine nutrient influx is essential for maintaining the balance and resilience of this complex salmon-driven ecosystem. Hísn̓ hold over in the K'vaí Lake during the summer before spawning in some tributaries in the (Atlas *et al.*, 2017).

### 2.1.3. K'vaí Salmon Ecosystem Study

A collaboration between the Hakai Institute, SFU and the Heiltsuk Integrated Resource Management Department (HIRMD) led to the K'vaí Salmon Ecosystem Study. This project revitalized weir building in the K'vaí River to monitor hísŋ abundance (Atlas *et al.*, 2017). To understand hísŋ salmon populations across their life cycle, two mark-recapture projects have been implemented since 2013. The first one focuses on estimating smolt abundance and marine survival; smolt are tagged at a smolt trap above tidewater, released upstream and recaptured in the smolt trap to estimate daily smolt outmigrant abundance. These tagged smolts are also recaptured or detected at in-river Radio Frequency Identification (RFID) antenna readers upon their return for mark-recapture estimates of smolt-to-adult survival. The second project tracks the survival of tagged hísŋ migrating from the K'vaí weir to their spawning grounds, above K'vaí Lake and uses mark-resight data from these tagged individuals to estimate annual spawner abundance (Figure 1). Through this long-term locally driven research, this work produces abundance estimates across the K'vaí hísŋ life cycle, key inputs to inform fisheries management (Atlas *et al.*, 2017, 2021).

There are two major developments in the K'vaí that offer emerging potential for salmon management. First, in recent years the Haílzaqv have increasingly used the weir as a terminal fishing site for small-scale subsistence harvest, providing a few hundred hísŋ annually for the community. Second, to integrate salmon monitoring and harvest, we installed cameras in the K'vaí weir to continuously monitor returning salmon. To enumerate the number of hísŋ that pass the weir, an artificial intelligence software has been developed in collaboration with SFU's Computing Science Department to identify and count salmon (Atlas *et al.* In review) This technological upgrade of the weir will enable in-season estimation of hísŋ abundance with potential to support adaptive in-season harvest management. Thus, one of the objectives of this project is to investigate the impact of in-season management on future hísŋ population trajectories.

## **2.2. Values-driven forward simulation**

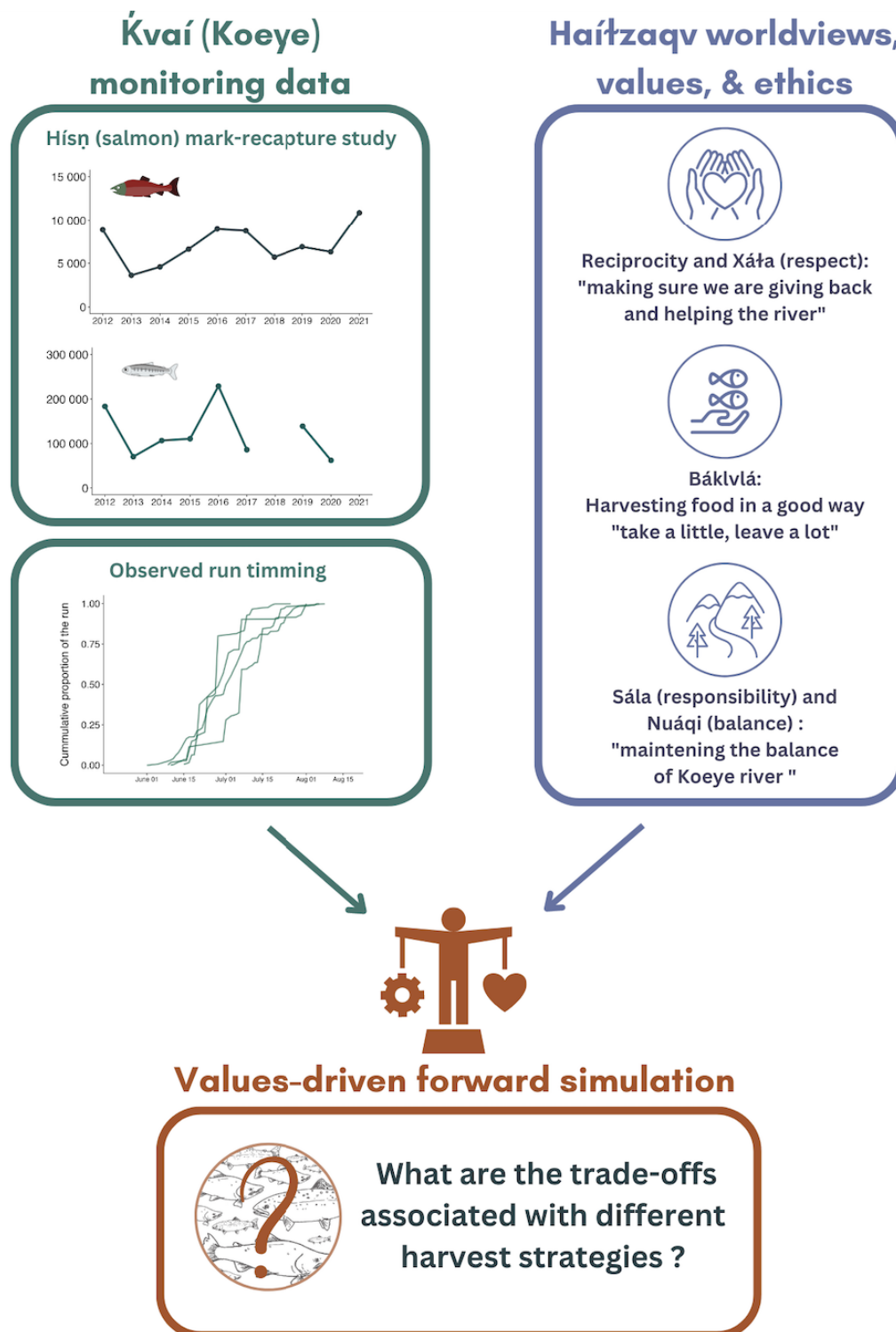
In this research project, we used a values-driven forward simulation to identify fishing thresholds and trade-offs among different harvest management strategies for the Kʷaí hísn̓ population (Figure 2). We applied the best practices of a management strategy evaluation suggested by Punt et al. (2016), by using a closed-loop simulation and Monte Carlo trials. One of the benefits of following such approaches is that it can evaluate trade-offs associated with different management strategies in face of uncertainty – such as parameter uncertainties or future changes in ecosystem productivity. To create a values-driven forward simulation, we used a participatory modelling approach that consisted of the following components: semi-structured interviews, a spawner-smolt recruitment model, and closed-loop simulation.

### **2.2.1. Participatory modelling approach**

Our goal was to co-create knowledge driven by HIRMD input, and for analyses to support management outcomes that would be beneficial for the Haíłzaqv Nation and the Kʷaí hísn̓ population. With the aim of co-producing knowledge that is culturally relevant to the Haíłzaqv Nation, we used a participatory modelling approach to develop the closed-loop simulation. A fundamental aspect of a participatory modelling approach is the involvement of the rights holders in the process of model development (Goethel, et al. 2019). To center the simulation on Haíłzaqv values, from conception to analysis, we had an iterative feedback process: we held several consultations with HIRMD managers to receive their feedback about simulation methods and technical choices made by the analyst team, such as simulation length, modelling scenarios and key uncertainties to be considered.

To create space for multiple knowledge systems and worldviews when co-producing knowledge, we conducted this research with an interpretative lens inspired by a knowledge pluralism framework, using Western scientific insights with Haíłzaqv values and ways of knowing (Cooke *et al.*, 2021). To do so, we - the analyst team, had to deliberately challenge our own biases and assumptions to avoid our epistemology to shape the way we generated knowledge. This introspective process led us -the analyst team, to educate themselves about decolonizing methods, indigenizing science, the colonial history of resources management, and the myriad cultures of Pacific Northwest

Indigenous people. Thus, across the different stages of this project, we aimed to work in collaboration with Haítzaqv experts and managers, and in addition to learn about cultural practices through a semi-structured interview process (see below).



**Figure 2.** Overview of the conceptual approach used to uphold and respect Haítzaqv worldviews when conducting value-driven forward simulation.

### 2.2.2. Semi-structured interviews

To understand what worldviews, governance principles, values, and management objectives should inform future food, social and ceremonial fisheries of hísn̄ in K̄vaí River system, we conducted semi-structured interviews using open-ended questions with two fisheries managers from HIRMD (Appendix E). Since all the questions were open-ended, we employed a thematic coding approach using Nvivo to summarize the key themes and objectives discussed during the semi-structured interviews. This process was approved by the Haítzaq nation through HIRMD research application, as well as Simon Fraser University 's office of research ethics (permit #30000130).

These interviews allowed us to have conversations on the socio-ecological system of the hísn̄ population in K̄vaí and the values and needs of Haítzaqv fisheries managers, so we (the analysts) had a better understanding of which processes and components of the "real" system should be modeled. The conversations were centred on identifying conceptual management objectives, harvest strategies and future climate change scenarios that should be explored in the forward simulation. For instance, HIRMD fisheries managers expressed that one of the fundamental Haítzaqv Ğvĩlá, laws of the ancestors, is Nuáqi or "to maintain the balance of the K̄vaí ecosystem" (Heiltsuk Tribal Council, 2018; Salomon *et al.*, 2023). People can enact this law by considering other predators impacts on hísn̄, such as seals or bears. Similarly, Bákvlá, a Haítzaqv word that means harvesting in a way that "takes a little and leaves a lot" (Brown, 2022), guided us when deciding the hísn̄ abundance targets, and the fishery mortality to consider in the simulation. While it would be impossible in the space of a few hours of conversation to grasp the extent of those nuanced Ğvĩlá laws, guiding principles that have evolved from millennia of oral histories, ceremonies, and cultural protocols, conversations with HIRMD staff were critical for articulating both qualitative values and quantitative benchmarks for hísn̄ conceptual objectives that were evaluated in our closed-loop simulation.

### 2.2.3. Conceptual objectives and associated operational objectives for K'vaí hísñ

Using interview results, we identified three conceptual objectives, and then determined associated operational objectives (Table 1). Operational objectives are conceptual objectives expressed in quantitative values or performance metrics (Punt et al., 2016). Follow-up conversations with HIRMD confirmed the consistency of these operational objectives with the conceptual objectives previously identified in the semi-structured interviews. Specifically, the Haítzaqv conceptual objectives that emerged from our interviews were (1) rebuilding the K'vaí hísñ population and maintaining the ecological role of the salmon population for long-term sustainability. Pending that, objective (2) báklvlá, to harvest hísñ from a sustainable population. The last objective (3) was to manage K'vaí hísñ fisheries as site-specific, with in-season adaptive management so Haítzaqv principles, such as Nuáqi (balance) and Xáta (respect), can be applied by knowing when, how and where hísñ are harvested.

For conceptual objective 1, we identified five operational objectives. The first operational objective is the mean abundance of the last 50 years of the simulation. The second one is the probability of the spawner population reaching  $S_{abundance}$  – the population abundance objective of the Koeye hísñ population. The third operational objective is the probability of recovery to spawner abundance at maximum sustainable yield ( $S_{msy}$ ). While there is no intrinsic biological justification to aim for  $S_{msy}$  other than "the more catch, the better" (Hilborn and Walters, 1992), a legacy from a neoliberal-value system, it theoretically indicates where the population can produce the most adult recruits per spawners, therefore, where the population will rebound from disturbance at the highest rate. Thus, it is a useful mathematical population dynamic metric to know (Walters, 2004). The fourth operational objective is the probability of reaching  $S_{gen}$ , the number of spawners that would result in recovery to  $S_{msy}$  in one generation in the absence of fishing. This benchmark has been found to be more robust to variability in population productivity than benchmarks based on a fixed proportion of  $S_{msy}$  (Holt et al., 2009; Holt and Bradford, 2011; Holt and Irvine, 2013). The fifth operational objective is the probability of extinction, defined as the probability of the population dropping below an extinction threshold of 5% of the equilibrium population size (Connors et al., 2020).

For conceptual objective 2, we identified four operational objectives. The first operational objective is the probability of overfishing. We quantified an overfishing state when the fishing mortality at time  $y$  population was higher than  $F_{msy}$ , the harvest rate at  $S_{msy}$ . The second operational objective is the probability of depleted population. We defined a depleted population as a population at time  $y$  that has a lower abundance than  $S_{msy}$ . The fourth operational objective is the mean annual catch, and the fifth operational objective is the proportion of years the fishery is open. Finally, we included the conceptual objective 3 – in-season management – as one of the major scenarios for harvest strategies, rather than as a metric of performance in meeting operational objectives.

**Table 1. Conceptual and associated operational objectives for the Kvaí hísñ fisheries.**

Conceptual objectives	Operational objectives
Rebuilding the Kvaí hísñ population and maintaining the ecological role of the salmon population for long-term sustainability	Mean Abundance Probability of recovery to $S_{abundance}$ Probability of reaching $S_{msy}$ Probability of reaching $S_{gen}$ Probability of extinction
Harvesting hísñ from a sustainable population. To respect báklvlá, the harvest only happens if the population is deemed sustainable	Probability of overfishing Probability of depleted population Mean catch Frequency of years fishery is open
Managing Kvaí hísñ fisheries as site-specific, with in-season adaptive management so Haítzaqv ancestral laws, principles and knowledges can be applied	Included as a harvest scenario

#### 2.2.4. Spawner-juvenile recruitment model

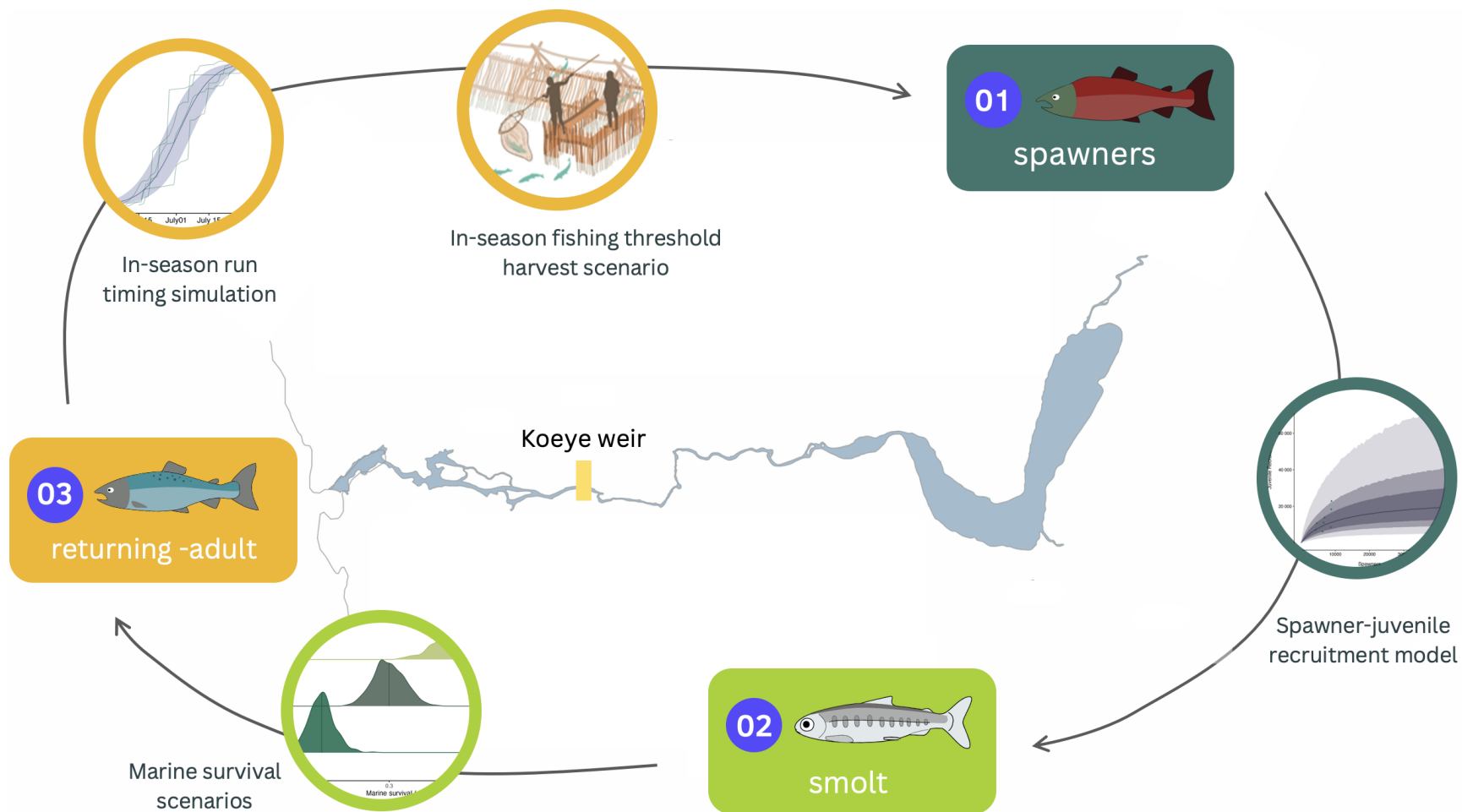
To estimate the spawner-recruitment relationship of the Kvaí hísñ population, we used a staged-structure model, following a Beverton-Holt (BH) recruitment relationship that assumes productivity remains unchanged over time (Fleischman et al, 2013, Stanton et al 2020). A BH relationship assumed a density-dependant mortality rate, thus

the recruitment increases toward an asymptote as the spawner population increases (Adkison, 2022). Consequently, the BH model is commonly used to represent how juvenile competition, such as competition for food or space, is driving the SR relationship and limiting the population abundance at the juvenile life-stage. We used the following equation (Hilborn and Walters, 1992):

$$R_y = \frac{\alpha S_y}{1 + \frac{\alpha}{\beta} S_y} + \varepsilon_y$$

where  $R_y$  is recruitment from brood year  $y$ ;  $S_y$  is spawner abundance at time  $y$ ;  $\alpha$  is the maximum rate of growth (productivity) at low stock size,  $\beta$  is the maximum number of recruits when  $S$  is large, and  $\varepsilon_y$  the mean zero random deviations from the expected recruitment function. We fitted this equation to a time-series of annual estimates of Kvaí spawner and smolt abundance from 2012-2021. For the purposes of our analysis, we assumed that all smolts leave Kvaí lake after one year of rearing, which is consistent with field data collections showing that 95-99% of hísŋ leave Kvaí as age-1 fish (W. Atlas *pers. comm.*).

The model was fitted in a Bayesian estimation framework using Markov chain Monte Carlo methods (implemented in STAN).  $\ln(\alpha)$  prior followed a normal distribution of 3, with a SD of 1. We used a vaguely informative  $\beta$  prior centered on the estimated habitat carrying capacity of the system (Atlas, 2019 [unpublished]),  $2.80000 \times 10^5$  with a standard deviation of  $1.4 \times 10^5$  (Appendix A, table 1). We examined convergence by looking at the Markov chains and the potential scale reduction factor ( $\hat{R}$ ). If ( $\hat{R}$ ) was less than 1.01, we assumed convergence.



**Figure 3. Overview of the closed-loop simulation on the Kvaí Hísni, for the in-season fishing threshold harvest scenario.** Salmon drawings made by Samantha Wilson, and they are used with permission of the artist.

### 2.2.5. Closed-loop simulation

To identify the trade-off amongst alternative harvest scenario amid swiftly changing climate conditions, we developed a stochastic, closed-loop simulation for Kvaí hísñ population (Figure 3). Each simulation scenario was iterated 500 Monte-Carlo trials for 75 years (therefore 10 generations of hísñ) to generate a posterior predictive distribution of the population abundance for each harvest strategy evaluated (Connors et al., 2020a). For each Monte Carlo trial, we drew from the Bayesian posterior distributions of the parameters from the alpha ( $\alpha$ ), beta ( $\beta$ ), and  $\sigma_R$  of the spawner- juvenile recruit model described above (section 2.2.4). The model included four sub-modeling components; i) an operating model representing salmon population dynamics, ii) a management procedure model that includes a forecast submodule and a iii) harvest strategy submodule and iv) an operational objective module that tracked the outcomes for associated harvest strategies. To capture the uncertainties associated with future climate-induced productivity changes, we evaluated alternative harvest strategies performance across different marine survival scenarios.

#### *Operating model and salmon population dynamics*

The operating model, a mathematical simplification of the true salmon population dynamics and the major components of the fisheries system, simulates the entire life cycle, from smolt to spawners, of the Kvaí River hísñ population over 75 years. Our operating model includes three stages; a recruitment model, an adult returns model, and a spawner model (number of adults that make it to the spawning grounds after local harvest).

First, the spawner-juvenile recruitment follows a stationary Beverton- Holt (BH) spawner-recruit model with random variation (Hilborn and Walters, 1992):

$$R_y = \frac{\alpha S_y}{1 + \frac{\alpha}{\beta} S_y} + \varepsilon^{\nu_y}$$

where  $R_y$  is recruitment from brood year  $y$ ;  $S_y$  is spawner abundance at time  $y$ ;  $\alpha$  is the maximum rate of population growth (productivity) at low stock size,  $\beta$  is the maximum number of recruits when  $S$  is large, and  $\nu$  reflects interannual variation in recruitment.  $\nu_y$  is assumed to be correlated ( $\phi$ ) over time:

$$v_y = \phi v_{y-1} + \varepsilon_y, \varepsilon_y \sim \text{Normal}(0, \sigma_R)$$

where  $v_{y-1}$  is the residuals of the predicted S/R from the previous year and  $\varepsilon_y$  is an independent, normally distributed process variation in survival, with the SD of  $\sigma_R$ .

Second, adult returns are defined by:

$$N_y = \sum_{a=4}^5 O_{y-a} \xi_{a-3}$$

in which  $N_y$  represents the total of adult returning to Kvaí river in year  $y$  as the sum of the proportion of individuals that return at age 4 and age 5 to the spawning grounds, based on the maturity schedule ( $\xi$ ). To represent the smolt-to-adult survival spawners ( $O_y$ ) we used the following equation:

$$O_y = U_y \times M_y \times R_y \times c$$

Where  $O_y$  is the total adults at year  $y$ ,  $M_y$  is the marine survival rate at time  $y$ ,  $U_y$  is the outmigration survival rate at time  $y$ ,  $R_y$  is the recruitment at time  $y$  and  $c$  is the constant commercial fisheries survival rate. We assumed total smolt-to-adult survival to be the same for year 4 and 5.

We incorporated variability within the outmigration survival of hísŋ smolts through the Koeve estuary, where  $U_y$  follow a lognormally distribution, with  $\bar{U}$  as the mean outmigration survival, and  $\sigma_U$  :

$$U_y \sim \text{LogNormal}(\bar{U}, \sigma_U)$$

The marine survival variation was generated as followed:

$$M_y \sim \text{LogNormal}(\bar{M} + m.\phi \cdot m.v, m.\sigma_\varepsilon)$$

Where  $M_y$  is lognormally distributed with  $\bar{M}$  as the mean marine survival,  $m.\phi$  as the expected marine correlation through time,  $m.v$  is the marine residuals of the previous year, and  $m.\sigma_\varepsilon$  is the marine survival deviation over the years. We chose a highly correlated  $m.\phi$  ( $r = 0.90$ ) based on explanatory simulations.

Finally, returning spawners for a given year  $y$  ( $S_y$ ) was then modeled as:

$$S_y = N_y - H_y$$

Where  $H_y$  is the harvested number of fish in a given year  $y$ . This value varied based on the harvest scenario described below. Furthermore, the reproductive success of small population size is known to decrease due to the allele effect and depensation (Liermann and Hilborn, 1997; Holt and Bradford, 2011; Connors et al., 2020). Hence, we set the quasi-extinction thresholds at 100 spawners to represent this reduction in reproductive success.

### ***Management decision model***

The management decision model assessed the harvest rate that will be applied to the returning population. It includes the forecast submodel, and the harvest strategy submodule.

**Forecast submodule:** The forecasting method employed to predict the run size that will return was determined by the specific harvest strategy.

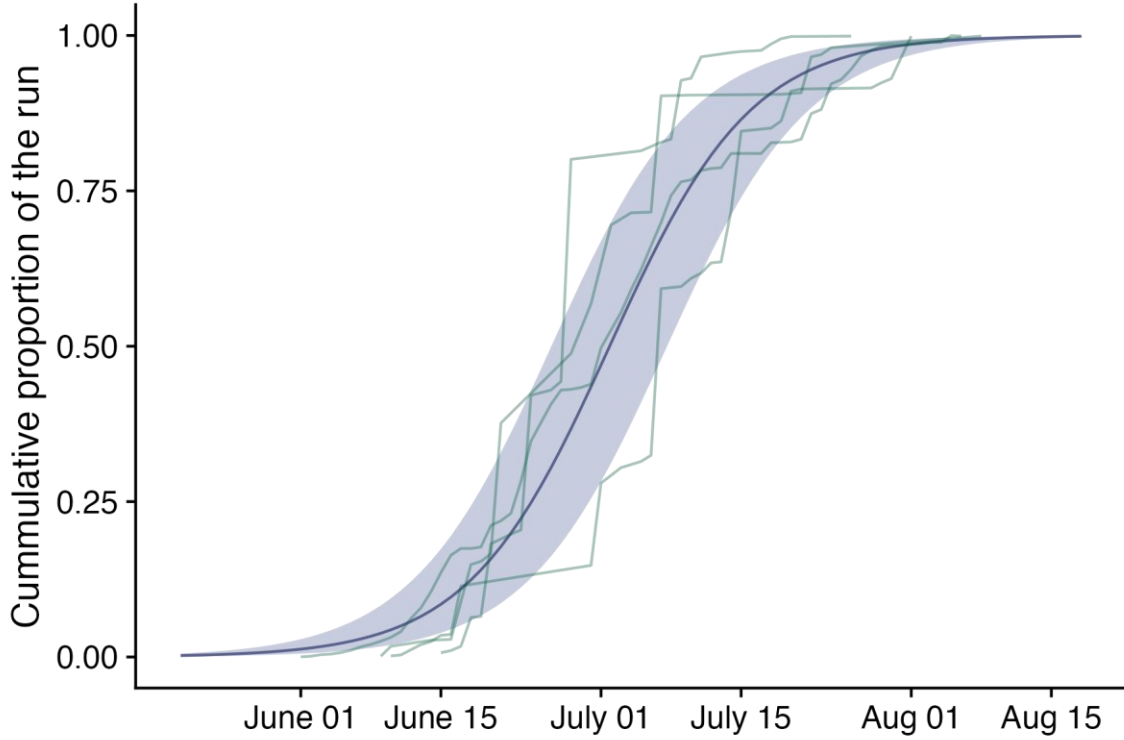
*Annual forecast model:* For the constant abundance strategy described below, we used an annual forecasting  $\widehat{N}_y$  :

$$\widehat{N}_y = \widehat{R}_{y-4} \times \overline{M} \times \overline{U} \times c$$

Where  $\widehat{R}_{y-4}$  is the predicted smolt recruitment,  $\overline{M}$  is the mean marine survival,  $\overline{U}$  is the mean outmigration survival, and  $c$  is the constant commercial fisheries harvest rate.

*In-season forecast model:* The in-season forecast model predicts the cumulative proportion of the total run past the weir as a function of calendar day (Figure 4). We fitted four years of cumulative proportion of tagged hísñ that passed the weir to a logistic model:

$$\text{logit}(\rho_d) = \varpi_{y_i} + \varphi_d$$



**Figure 4. Estimated run timing for the Kvaí hísñ**

Estimated relationship between date and the proportion of the Kvaí River hísñ run past the Kvaí weir with 95% credible intervals from the Bayesian state-space model. Each green line is an observed run timing for the year 2017,2018,2019 and 2020.

where  $\rho$  is the cumulative proportion of tagged hísñ for calendar  $d$ ,  $\varpi$  is the random intercept of year for year  $i$ , and  $\varphi$  the estimated coefficient of calendar  $d$ . The model was fitted in a Bayesian estimation framework using Markov chain Monte Carlo methods (implemented in BRMS). To see the prior distributions for the model parameters, see the appendix A.

We simulated run timing for each year of every simulation iteration by sampling from the posterior distributions of the cumulative run-timing model. We generated observations errors to the simulated cumulative number of hísñ that pass the weir ( $C_d$ ) to represent uncertainty around the observed hísñ passage from the in-season camera-trap monitoring at the weir using:

$$\widehat{C}_d \sim \text{Normal}(C_d, cv)$$

where  $\widehat{C}_d$  is the simulated “observed” cumulative hísñ passage to calendar day  $d$ , normally distributed with an SD of  $cv$ . To forecast the total run abundance for calendar  $d$

$(\widehat{N}_d)$ , we followed similar methods of (Catalano and Jones, 2014) using this mathematical formula:

$$\hat{i}_d = \frac{\hat{C}_d}{P_d}$$

$$\widehat{N}_d = median(\hat{i}_d)$$

where  $P_d$  is the posterior distributions of the cumulative passage for calendar day  $d$ , and  $\hat{i}_d$  is the posterior predicted distribution of the forecasted run for calendar day  $d$ . We used the median value of  $\hat{i}_d$  as the in-season forecasted run  $\widehat{N}_d$ .

**Harvest strategy submodule:** To implement the different harvest strategies for the FSC hísñ fisheries in the simulation, we used a harvest control rule, an algorithm defining if fishing happens and by how much. We identified harvest strategies that HIRMD fisheries managers were interested in during the semi-structured interviews. They asked for a harvest catch that could be adapted weekly based on the in-season run. Thus, based on HIRMD guidance, we chose a fishing threshold strategy that specified a spawner abundance threshold ( $S_{\text{Fishing}}$ ) below which fishing is prohibited (Free *et al.*, 2022).

To transform this harvest strategy into an in-season adaptative one, we updated the harvest management decision every week of the simulated fishing season. If the in-season forecasted run model for that week projected a forecasted run ( $\widehat{N}_d$ ) exceeding  $S_{\text{Fishing}}$ , harvest was permitted ( $H_y$ ). In that case, a maximum allowable catch ( $MAC_{\text{week}}$ ) was applied for that week. This  $MAC_{\text{week}}$  value was necessary to spread the harvest throughout the season to protect the genetic diversity of the Kvaí population. Additionally, it reflects báklvlá “take a little, leave a lot”, a Haítzaqv principle talked in the semi-structured interviews. Once the catch number reached the annual MAC in a given simulation, the harvest was not permitted anymore, regardless of if the forecasted run size for that week was higher than  $S_{\text{Fishing}}$ .  $MAC_{\text{week}}$  number is based on exploratory simulations that showed the best combination of weekly MAC for each annual MAC (see Appendix B). Furthermore, the simulated fishing season spanned from June 16<sup>th</sup> to August 15<sup>th</sup> based on previous run timing (Figure 4). However, early in the fishing season, the in-season forecast ( $\widehat{N}_d$ ) is likely to overestimate the total abundance run

since few fish have passed the weir at that time. Therefore, for the in-season harvest strategy, fishing is prohibited the two first weeks to avoid overfishing.

To identify the benefits associated with an in-season fishing threshold strategy for the Kvaí hísþ population, we compared it to two alternative harvest strategies: a constant catch strategy, and a constant abundance strategy (Free *et al.*, 2022). Currently, HIRMD manages the FSC fisheries in its territory using a constant catch strategy (Table 2.1). This strategy allows the same total catch (TC) to be annually harvested, regardless of the forecasted run. Thus, it can be useful for a data-limited population; it avoids the need for a population assessment. It also can provide more stable catches. A constant abundance strategy (Table 2.2) holds the population at a set abundance target ( $S_{\text{target}}$ ) by harvesting the difference between the annual forecasted run ( $\widehat{N}_y$ ) and  $S_{\text{target}}$ .

**Table 2. Alternative harvest strategies (constant catch, constant abundance and in-season fishing threshold) and associated harvest control rule considered in the closed-loop simulation for the Kvaí hís population. A harvest control rule defines management action.**

Harvest strategy	Harvest control rule*	Associated graph
1) Constant Catch	$H_y = \text{Total Catch (TC)}$	
2) Constant Abundance	$H_y \begin{cases} 0 & \text{if } \hat{N}_{y-4} < S_{target} \\ \hat{N}_{y-4} - S_{target} & \text{if } \hat{N}_{y-4} > S_{target} \end{cases}$	
3) In-Season Fishing Threshold	$H_w \begin{cases} 0 & \text{if } \hat{I}_d < S_{fishing} \\ MAC_{week} & \text{if } \hat{I}_d > S_{fishing} \end{cases}$ $H_y = \sum_{w=2}^9 H_w$	

\*See special terms and symbols on page xi

**Table 3. Parameters used in the values-driven simulation**

Symbol	Description	Numerical value	Justification
<b>Closed-loop parameters</b>			
$\widehat{C}_d$	Simulated “observed” cumulative hísṇ passage to calendar day $d$	-	-
$\hat{t}_d$	Posterior predicted distribution of the forecasted run for calendar day $d$	-	-
$\widehat{N}_d$	In-season forecasting at calendar day $d$	-	-
$\widehat{N}_y$	Annual forecasting at year $y$	-	-
$C_d$	Simulated cumulative number of hísṇ that pass the weir	-	-
$H_y$	Harvested number of fish in a given year $y$	-	-
$\overline{M}$	Mean marine survival	0.15, 0.25, 0.30, 0.35	HIRMD input (see appendix C)
$N_y$	Total of adult returning to Kvaí river in year $y$	-	-
$P_d$	Posterior distributions of the cumulative passage for calendar day $d$	-	-
$R_y$	Juvenile recruitment from brood year $y$	-	-
$S_y$	Spawner abundance at time $y$	-	-
$S_y$	Returning spawners for a given year $y$	-	-
$\overline{U}$	Mean outmigration survival	0.25	(Quinn, 2018) (see appendix C)
$\varepsilon_y$	Normally distributed stochastic deviations in recruitment	-	-
$\sigma_R$	Recruitment white noise process SD for recruitment $R$	Posterior distribution of sigma in the spawner-recruit model	-
$\sigma_U$	SD of the mean outmigration survival	0.10	Sensitivity analyses
$c$	Constant commercial fisheries survival rate	0.95	Explanatory simulation (W. Atlas <i>pers. comm.</i> )
$cv$	Standard deviation of simulated “observed” cumulative hísṇ passage to calendar day $d$	50	Explanatory simulations
$m. \nu$	Marine residuals of the previous year	-	Explanatory simulations
$m. \sigma \varepsilon$	Random marine survival deviation	0.05	Explanatory simulations

$m, \phi$	Expected marine correlation through time	0.90	Explanatory simulations
$M_y$	Marine survival rate at time $y$	-	-
$N_y$	Total of adult returning to Kvaí river in year $y$	-	-
$O_y$	Smolt-to-adult survival spawners	-	-
$U_y$	Outmigration survival rate at time $y$	-	-
$\alpha$	Maximum rate of population growth (productivity) at low stock size	Posterior distribution of alpha in the spawner-recruit model	-
$\beta$	Maximum number of recruits when $S$ is large	Posterior distribution of beta in the spawner-recruit model	-
$\xi$	Maturity schedule	$a_5 = 0.35$ $a_4 = 0.65$	Scale collection of Kvaí hísu from 2013-2019.
$v$	Interannual variation in recruitment (i.e., noise)	-	-
$\phi$	Temporal correlation in recruitment	0.23	(Connors et al, 2020)
<b>Harvest parameters</b>			
$MAC_{\text{annual}}$	Maximum number of fish that can be removed from the sockeye population within a year, used in the in-season harvest strategy	500, 1000, 2000, 3000	Sensitivity analyses (see appendix B)
$MAC_{\text{week}}$	Maximum number of fish that can be removed from the sockeye population within a week, associated with a $MAC_{\text{annual}}$	100, 200, 200, 250	Sensitivity analyses (see appendix B)
$S_{\text{abundance}}$	Population abundance objective for the Koeve sockeye population		HIRMD input
$S_{\text{fishing}}$	Spawner abundance fishing threshold below which fishing is prohibited, used in the in-season fishing threshold harvest	4000, 6000, 7500	HIRMD input
$S_{\text{target}}$	Abundance target for the spawner population used in the constant abundance harvest strategy	4000, 6000, 7500	HIRMD input

## ***Operational objectives module***

The operational objective module is one of the essential components of a closed-loop simulation as it tracks the outcomes of the different harvest strategies to summarise their ability to reach the management objectives. Operational objectives are conceptual objectives expressed in quantitative values or performance metrics (Punt *et al.*, 2016). The choice of performance metrics is highly subjective and values-driven, meaning the analyst's unconscious biases will influence those decisions unless they are intentionally addressed during the modeling co-development process. Hence, we generated a list of potential performance metrics to present to our HIRMD research collaborators for them to further refine. We presented performance metrics that could align with core Hałřzaqv perspectives and values (see Table1), which we discussed in the semi-structured interviews. Based on this process, we identified performance metrics for each conceptual objective. We then calculated the performance of operation objectives as the mean proportion of the last 25 years of the simulation for each Monte Carlo trial that met the specific operational objectives.

## ***Climate-induced scenarios***

During our conversations with HIRMD managers, they expressed concerns about climate change impacts on *Kvał hřř salmon*. Accordingly, we collaboratively identified several climate change scenarios for the forward simulation. Warming of the oceans will likely have negative impacts on salmon survival at sea (Cavole *et al.*, 2016; Grant, MacDonald and Winston, 2019; Lindley *et al.*, 2021). Yet, it is difficult to predict the magnitude of this decline and hence adapt management strategies pre-emptively to those changes. Therefore, we evaluated how robust the performance of a harvest strategy was across different marine survival rate. Four different marine survival rates were incorporated in the forward simulation by changing the mean rate of survival  $\widehat{M}$  15 %, 25 %, 30 %, and 35 %, for a respective smolt-to-adult survival of 3.5 %, 6.2 %, 7.5 %, 8.7 %, respectively.

### **2.2.6. Weighted composite table**

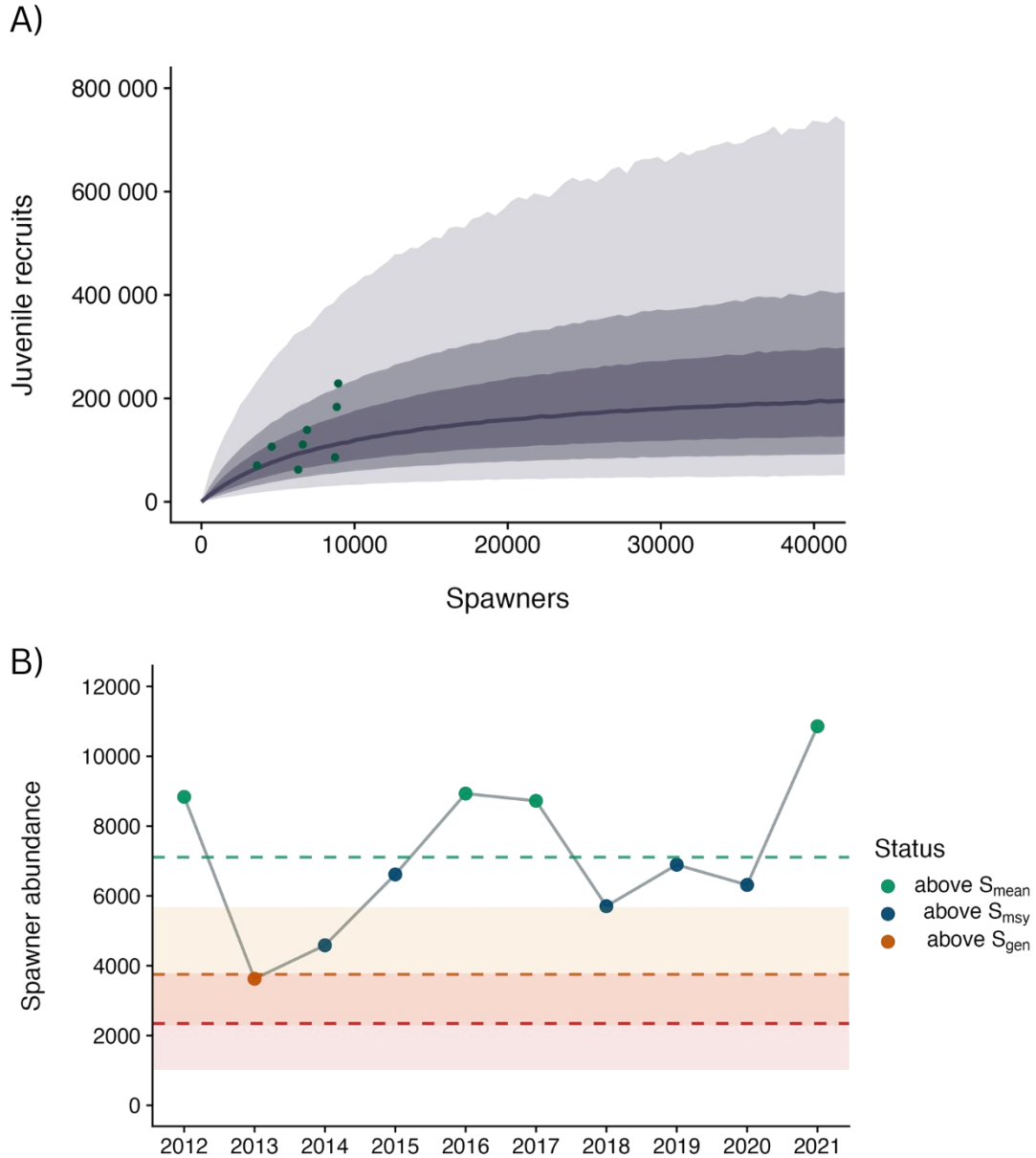
The outcomes from this analysis include a series of management objectives and their associated values. To be able to compare between different scenarios using the different operational objectives, we needed to find a way to combine the various metrics

to have one single output value for each harvest scenario. To do this, we used a weighted composite table following similar methodologies to (Fulton *et al.*, 2014). This method allowed for management objectives (and the value system they draw upon) to be integrated explicitly into the trade-off simulation. First, we normalized the mean performance for each operational objectives for the last 25 years of the simulation to get values ranging from 0 to 1. For the operational objectives where a lower probability was a more desirable result than a higher probability (e.g., probability of extinction), we subtracted the mean performance to 1 and then normalised it. Second, we weighted each operational objective based on two different fisheries policies (value ranging from 0 to 1.5). The first fisheries policy reflects the management priorities expressed by HIRMD during our semi-structured interviews, whereas the second one is based on a contemporary 'business-as-usual' fisheries policy that prioritized economic objectives. Third, we summed up all the weighted performance to get one single value, which we will call a composite score. Finally, to facilitate the comparison between composite scores, we normalized them across all harvest strategies, so the highest composite score had a value of 1, and all other values are scaled accordingly. This means that the harvest strategy that performed the best had a value of 1.

### 3. Results

#### 3.1. Population dynamics of *Kvaí hísni*

We estimated the model parameters of the *Kvaí hísni* spawner- juvenile recruit relationship for the time series from 2012-2021 (Figure 5A). The predicted equilibrium population size was 277,600 juvenile recruits (median  $\alpha = 30.6$  recruits/spawner, 90 % CI = 24.8 – 48.7; median  $\beta = 277,633$ , 90 % CI = 144,385 – 433,454). At the time of the spawner/recruit analysis, we were missing smolt recruitment for two spawner cohorts (2018 and 2021), consequently, we have eight data points of spawner/recruit data. We estimated  $S_{msy}$ , the spawner abundance predicted to maximize long-term yield from the system under equilibrium conditions (Hilborn and Walters, 1992), for a smolt-to-adult survival of 8 % (Figure 5B) to be 3,760 (with 95 % CI= 2282- 5675). We estimated  $S_{gen}$ , the spawner abundance that will result in recovery to  $S_{msy}$  within one generation under equilibrium conditions, to be 2,357 (with 95 % CI= 1,000-3,800). The mean spawner abundance between 2012-2021 for *Kvaí hísni* is 7100 fish.



**Figure 5. Population dynamics of Kvaí hísñ**

A) Estimated relationship between juvenile recruitment and spawner abundance of the Kvaí hísñ for 2012-2020. Purple polygons are the 50<sup>th</sup> (dark purple), 75<sup>th</sup> (medium purple) and 95<sup>th</sup> (light purple) credible intervals predicted between spawner abundance and recruitment based on 40 000 random draws from the posterior distributions of the spawner-recruit relationship with a log-normal recruitment variation to illustrate uncertainty and random variation. B) Estimated spawner abundance from time series 2012-2021 with credible intervals of 95 % for spawner abundance at maximum sustainable yield ( $S_{msy}$ ) and spawner abundance that will recover to  $S_{msy}$  within one generation ( $S_{gen}$ ). The green dots represent a population abundance above the  $S_{mean}$ , the blue dots represent a population above  $S_{msy}$  and the orange dots are above  $S_{gen}$ .

## 3.2. Results from the closed-loop simulation

Here, we focus our results on the three overarching conceptual objectives for the Kvaí hísñ: (1) rebuilding the Kvaí hísñ population and maintaining the ecological role of the salmon population for long-term sustainability; (2) harvesting hísñ from a sustainable population; (3) managing Kvaí hísñ fisheries as site-specific, with in-season adaptive management so Haítzaqv ancestral laws, principles and knowledges can be applied. For each of these objectives, we explored the impacts of management strategies on the probability of achieving the operational objectives (Table 2).

### 3.2.1. Effects of harvest strategies and climate mediated marine survival on population abundance and extinction risk (Objective 1)

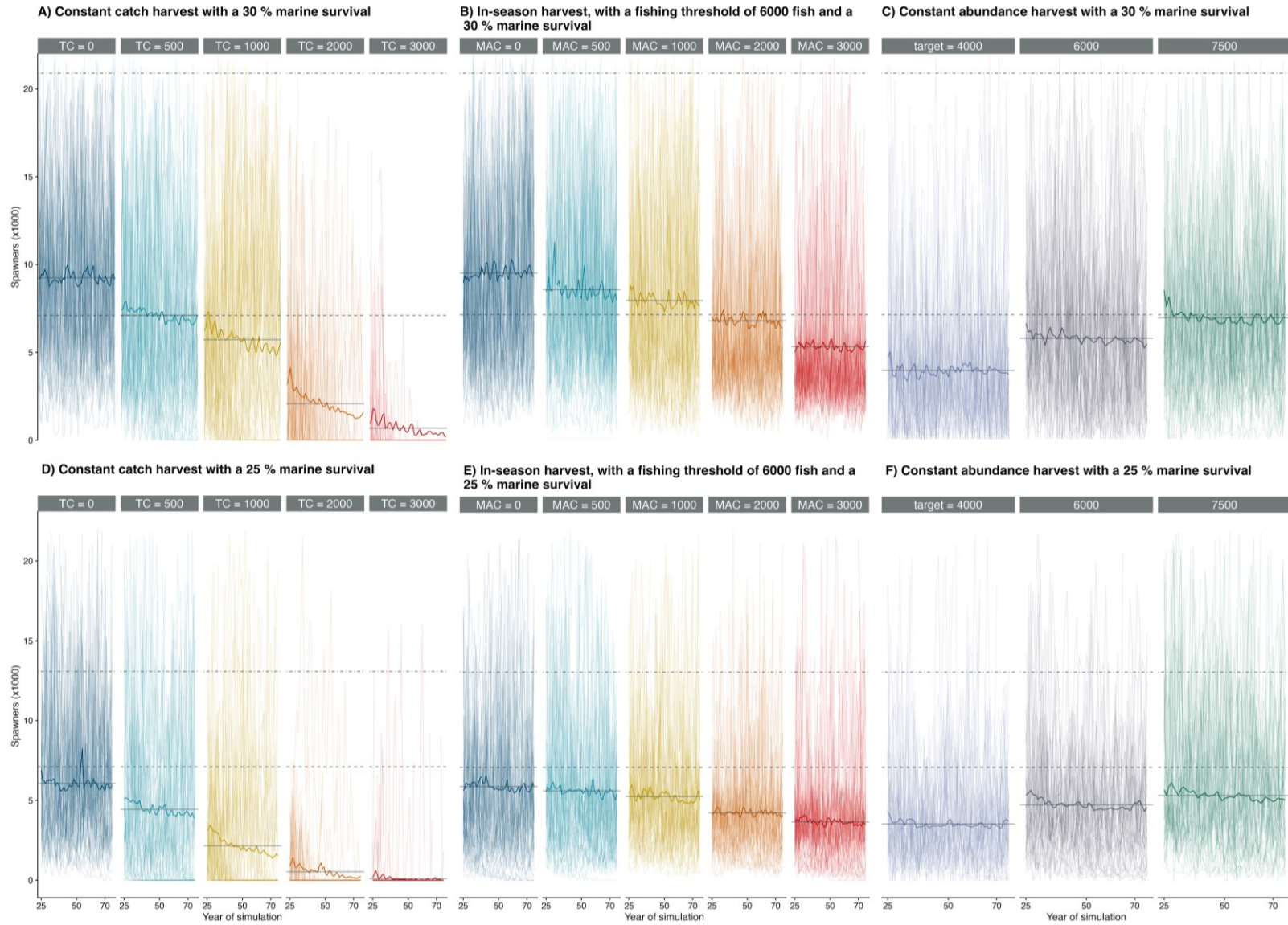
We quantified the impact of harvest strategies on population size and extinction risk (conceptual objective 1; Rebuilding the Kvaí hísñ population and maintaining the ecological role of the salmon population for long-term sustainability).

In the constant catch strategy, we found that increasing the total catch number (TC) decreased the mean spawner population abundance (Figures 6A & 6D). For a no fishing scenario with a marine survival rate of 30%, the mean spawner abundance was 9300 fish (panel A, TC = 0, straight grey line). However, in a total catch scenario of 1000 (TC = 1000) the mean spawner abundance was 5700 fish, while in a 3000 fish total catch scenario (TC = 3000) mean spawner abundance was 650 (Figures 6A). Importantly, when comparing the baseline mean abundances of a lower marine survival scenario (25%), there was a drastic decrease in mean abundance as total catch increased (Figure 6D). Under this lower marine survival scenario, mean spawner abundance decreased from 6000 fish (TC = 0) in a no fishing scenario, to 2200 fish (TC = 1000) to 100 fish (TC = 3000). Furthermore, even the lowest total catch scenario (TC = 500) for the 25% marine survival rate resulted in an increase in the risk of extinction as the majority of the Monte-Carlo trials went extinct. Therefore, there is an increased risk of extinction for constant catch strategies higher than 500 when marine survival rates are 25%.

Fisheries harvest under the in-season management strategy (Figures 6B & 6E) had smaller declines in abundance and did not increase extinction risk. For instance, for a

marine survival rate of 30 %, the mean spawner abundance decreased from was 9 400 (MAC = 0) when MAC was 0 to 8 000 for a maximum allowable catch of 1000 (MAC = 1000), and 5200 fish when MAC was 3 000 (MC = 3000). In contrast, at a marine survival scenario of 25%, there was a minor decrease in mean abundance between the no catch scenario (5900 fish) and the other maximum allowable catch numbers. At maximum allowable catches of 1000 and 3000, we found the mean spawner abundances to be 5300 and 3700 fish respectively. However, this fishing threshold strategy produced very few Monte-Carlo trials that resulted in population extinctions across all of the catch and survival scenarios.

For the constant abundance strategy, mean spawner abundances declined as the population abundance target decreased, while the risk of extinction stayed the same across population abundance target options (Figure 6C & 6F). These results were robust to scenarios of lower marine survival. Even with a marine survival of 25 %, the constant abundance harvest still maintained average spawner abundance above 4000 fish. Overall, the in-season and constant abundance harvest strategies outperformed the constant harvest strategy, with a lower risk of extinction, and higher overall population abundance.



**Figure 6. Effect of harvest strategies and marine survival rates on population abundance and extinction risk**

Simulated mean spawner abundance over time (numbers of fish; solid colored lines) for two marine survival scenarios (30%, top row; 25%, bottom row) as a function of key harvest strategies (constant catch harvest, first column; in-season fishing threshold of 6000 fish, second column; constant abundance harvest, third column) and Total Catch (TC; colored panels showing ascending TC values from blues to reds) , Maximum Allowable Catch(MAC, colored panels showing ascending MAC values from blues to reds) or abundance target(target, colored panels showing ascending target values from light purple to green). Panels also include 50 randomly drawn individual simulations for each harvest strategy settings (pale lines). The grey lines are the overall mean of the time-series of the mean spawner abundance for each individual harvest. Dashed horizontal lines are included to aid interpretation across panels, denoting current spawner abundance mean of 7100 (lower long dots line), and the maximum spawner capacity of 20,900 fish for the 30% marine survival panels, and 13,072 for the 25% marine survival panels.

### 3.2.2. Effects of harvest strategies and marine survival on reaching $S_{\text{gen}}$ and $S_{\text{abundance}}$ (Objective 1)

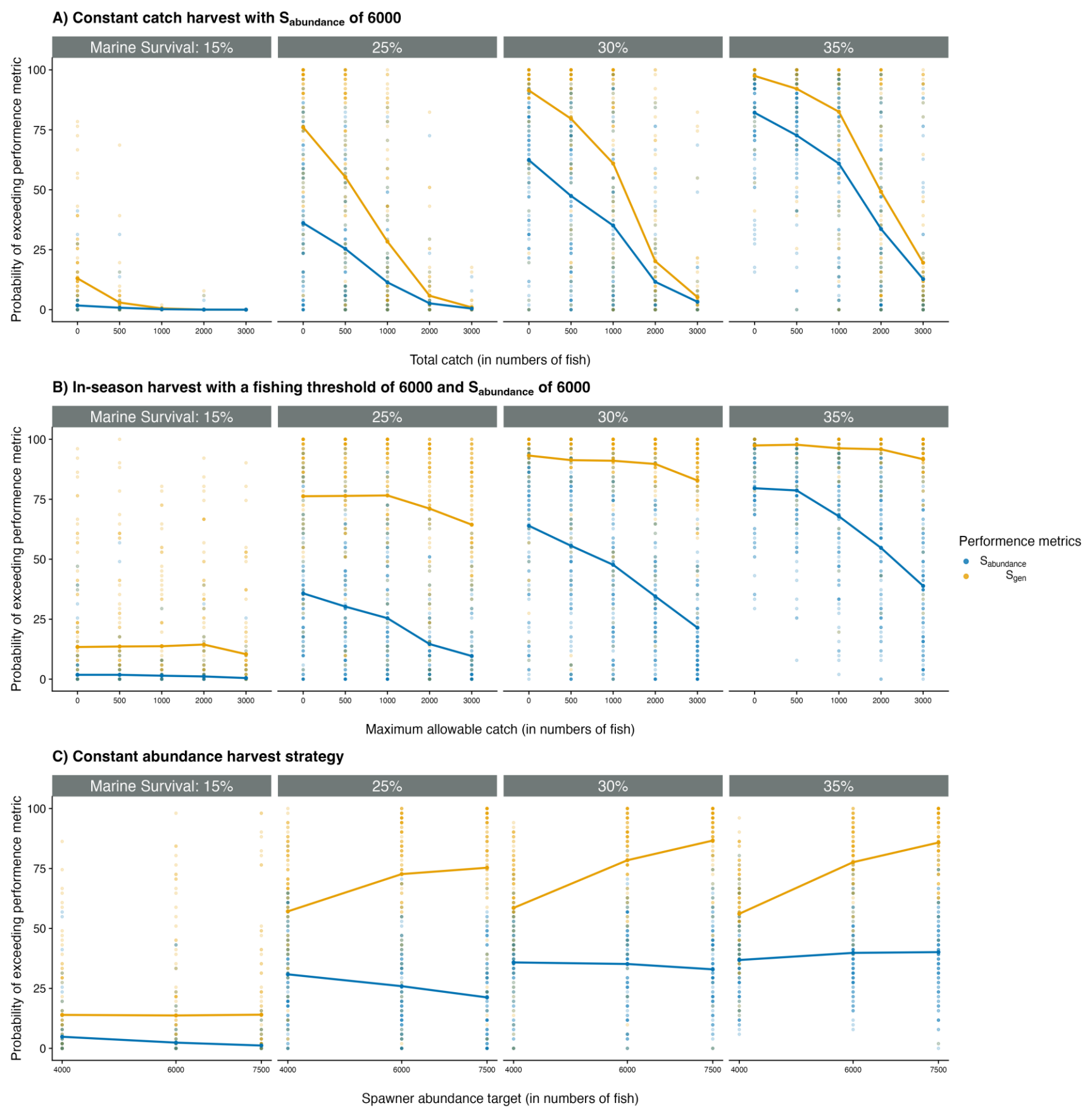
We compared the performance and sensitivity of our closed-loop simulation for meeting the operational objectives  $S_{\text{gen}}$  (spawner abundance that will lead to maximum sustainable yield within one generation in the absence of fishing) and  $S_{\text{abundance}}$  (population abundance objective for the Koeye hísñ population) across alternative climate change and harvest scenarios. Since there is always a risk associated with stochastic mortality events in a fisheries system regardless of the harvest scenarios, we compared the performance of the harvest scenarios to the "zero-harvest" scenario ( $\text{MAC} = 0$ ).

Across all harvest scenarios, the probability of reaching  $S_{\text{gen}}$  and  $S_{\text{abundance}}$  mirrored similar trends: they declined as the harvest mortality increased. However, these effects varied across harvest strategies, with constant catch strategy having the biggest decline in the probability of meeting these operational objectives as harvest mortality increased. For instance, in the baseline "zero-harvest" scenario, the simulated populations reached  $S_{\text{gen}}$  90 % of the time for the marine survival rate of 30%. With the same marine survival rate, in the constant catch strategy, even a small total catch (e.g.  $\text{TC} = 500$ ) lowered the probability of reaching  $S_{\text{gen}}$  to 75 % (Figure 7A). By contrast, in the in-season harvest population reached  $S_{\text{gen}}$  for 90 % of the time for most of the maximum allowable catch options (e.g.,  $\text{MAC}=500$  to  $\text{MAC} = 2000$ ) (Figure 7B), while in the constant abundance strategy, the probability that the Koeye hísñ population exceeded  $S_{\text{gen}}$  was 80 % for an spawner abundance target of 6000 (Figure 7C).

Furthermore, lower marine survival rates reduced the probability of reaching  $S_{\text{gen}}$  and  $S_{\text{abundance}}$  for all harvest strategies. As a comparison, the baseline "zero-harvest" scenario for a marine survival rate of 30% went from 90% to reach  $S_{\text{gen}}$  to 75% in the marine survival rate of 25%. The constant catch strategy went from reaching  $S_{\text{gen}}$  75% to 30% for a total catch of 500 fish (Figure 7A). In the in-season harvest strategy and the constant abundance target of 6000 fish, most of the harvest catch options reached  $S_{\text{gen}}$  75%, similarly to the baseline "zero-harvest".

Importantly, only in the in-season harvest strategy, harvest mortality had a greater effect on the probability of reaching  $S_{\text{abundance}}$  than on reaching  $S_{\text{gen}}$ , across all

marine survival scenarios (Figure 7B). Indeed, as MAC increased, the percentage of simulated years that the population reached  $S_{abundance}$  decreased drastically. For example, it decreased from 75 % in a no fishing scenario, to 50 % (MAC = 1000) to 25 % (TC = 3000). Thus, in-season harvest strategy negatively impacted the probability of reaching an abundance target objective at higher MAC values. Overall, high abundances were more likely to exceed the two operational objectives  $S_{gen}$  and  $S_{abundance}$  under the in-season harvest strategy than under constant catch harvest and constant abundance harvest across all marine survival scenarios.

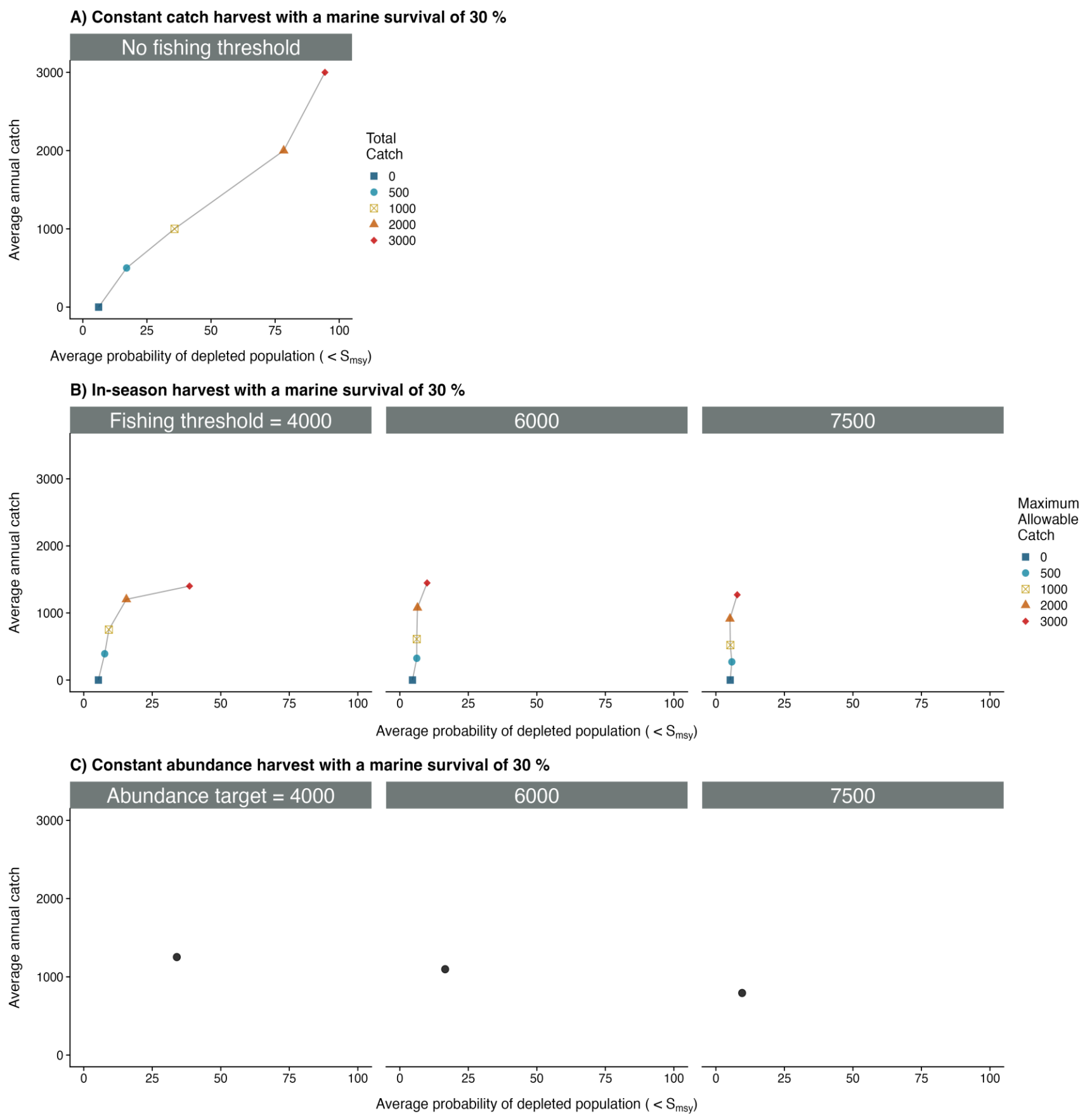


**Figure 7. Effects of harvest strategies and marine survival on reaching  $S_{gen}$  and  $S_{abundance}$**   
Mean probability of reaching the performance metrics  $S_{abundance}$  (blue line, candidate benchmark for spawner abundance target) and  $S_{gen}$  (yellow line, probabilities of recover to the spawner abundance at maximum sustainable yield,  $S_{msy}$ , in one generation) for key harvest strategies (constant catch top row, in-season middle row, and constant abundance bottom row) as a function of marine survival scenarios (in columns) when the candidate abundance target is of 6000 fish for in season harvest and constant catch harvest. The bottom row shows the same metrics but for spawner abundance targets of 4000, 6000 and 7500. The mean probability was calculated as the mean proportion of the last 25 years of the simulation for each Monte Carlo trial that met the specific operational objectives. Panels also include 100 randomly drawn simulation results for each harvest strategy settings (blue and yellow points for  $S_{abundance}$  and  $S_{gen}$ , respectively)

### 3.2.3. Effect of harvest strategies on mean annual catch and depletion risk (Objective 2)

To explore trade-offs between harvest and conservation risks, we compared the long-term mean annual catch to the probability of depleted population (spawner abundance lower than spawner at maximum sustainable yield) across all scenarios under the marine survival rate of 30 % (Figure 8).

Generally, increasing the harvest mortality (e.g. total catch or maximum allowable catch) increased the mean catch and the probability of depleting the hisn population. However, the magnitude of these trade-offs varied across harvest scenarios. In the constant catch strategy, increasing total catch (TC) numbers increased mean catch, but at the expense of increased risk of depleted population (Figure 8A). For example, at a total catch of 500 and 3000, 20 %, and 90 % of the simulated population abundances were lower than  $S_{msy}$ , respectively. Under the in-season harvest scenario, such trade-offs between catch and depleted population were not discernable (Figure 8B). Indeed, higher harvest mortality slightly increased the average catch, but the risk of depleted population did not increase considerably at higher MAC values (between 5 % - 15%). Higher fishing threshold didn't reduce the probability of depleted population. For the constant abundance strategy, increasing abundance targets ( $S_{target}$ ) resulted in a marginal decrease of depletion risk and mean catch (Figure 8C). Overall, the magnitude of trade-offs between mean annual catch and depletion risk were the greatest under a constant catch harvest scenario.



**Figure 8. Trade-offs between mean catch and the average probability of depleted population ( $S < S_{msy}$ ) among harvest strategies.**

A) Constant catch harvest as a function of a total catch number ranging from 0 to 3000. B) In-season harvest as a function of fishing threshold (4000,6000,7500) and maximum allowable catch (MAC)(from 0 to 3000). A fishing threshold indicates the spawner abundance at which harvest is allowed, while MAC is the maximum harvest mortality that can be applied annually. C) A constant abundance harvest as a function of abundance target (4000,6000, 7500). Predicted average catch was measure as the total mean of each Monte-Carlo trial's catch average (500 in total). Average probability of depleted population as the mean proportion of the last 25 years of the simulation for each Monte Carlo trial that was below  $S_{msy}$ . Contrasting strategies between and among panels shows trade-offs between conservation and catch. This figure only show the marine survival scenario of 30 %.

### 3.2.4. Effect of harvest strategies on population status (Objective 2)

We examined conceptual objective #2 (to harvest h́sn from a sustainable population) by evaluating the effects of harvest strategies on population status relative to spawner maximum sustainable yield ( $S_{msy}$ ) and harvest rates relative to fishing mortality producing the maximum sustainable yield ( $F_{msy}$ ) for the simulated years 25-75 of each Monte Carlo trial. Thus, each point in Figure 9 represents a year from all the combined Monte Carlo trials for a 30 % marine survival climate scenario. We plotted these results across four quadrants of a Kobe plot, with each quadrant representing a population outcome falling into four general status categories (Figure 9A); (1) unsustainable status: population is depleted and overfishing is occurring (red), (2) population is above  $S_{msy}$  but overfishing is occurring (orange), (3) population is depleted, but fishing mortality allows population to grow (green), (4) sustainable population status with fishing mortality allowing population to grow (blue). It is worth mentioning that the line that defines depletion could be moved depending on the needs and priorities of the fisheries managers. To align our assessment of management performance with HIRMD's objective to harvest only from a sustainable population, points must fall in the category 4 to be considered "sustainable".

We found that in-season harvest strategy significantly lowers the risk of overfishing. Indeed, under an in-season harvest strategy, the h́sn population is almost always within the desired sustainable status (Figure 9C). On the other hand, the constant abundance strategy increases the risk of overfishing and the population to be overfished (Figure 9D). For instance, most of the points are in the unsustainable or overfishing zone, with a higher density of points where the harvest decimated the population (top left corner within one Kobe graph, where the  $S/S_{msy}$  is 0 but the  $F/F_{msy}$  is high). Likewise, the constant catch strategy increases the risk of overfishing the population (Figure 9B). The population is just as likely to fall in the overfished category than to be in the sustainable category when the total catch (TC) is at 2000 fish, which is approximately the current  $F_{msy}$ . In summary, the main drivers of the population status were the type of harvest strategy and the fishing mortality (e.g. TC and MAC).



**Figure 9. Effect of harvest strategies on population status**

A) A kobe graph of four conservation population status; (1) unsustainable: population is depleted and overfishing is occurring (red), (2) population is above  $S_{msy}$  but overfishing is occurring (orange), (3) population is depleted, but fishing allows population to grow (green), (4) sustainable population, fishing allows population to grow (blue). B) constant abundance strategy as function of abundance threshold. C) constant catch strategy as a function of total catch (TC). D) In-season harvest strategy as a function of fishing threshold(columns) and maximum allowable catch (MAC, rows), and (TC, rows). Each dot represents a year in a simulation, and every Monte-Carlo simulation is shown. We showed the simulated years from year 25th to year 75th for all Monte Carlo trials, so each point is one individual year. The colors of the points represent the harvest strategy type; constant abundance is orange; grey is constant catch and blue is in-season harvest strategy.

### 3.2.5. Integrated Trade-off analysis

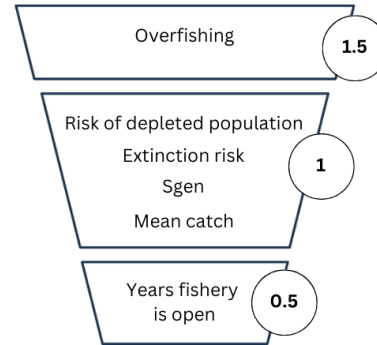
The composite table reflecting HIRMD's articulated needs revealed that the in-season harvest strategy was the highest-performing harvest strategy (Figure 10A). We found that when associated with an in-season harvest strategy, the performance of the harvest strategy was not particularly sensitive to the fishing threshold when the maximum allowable catch (MAC) was lower than 2000. All the scenarios under a constant catch harvest strategy performed poorly, except when the total catch (TC) was 500. A total catch of 500 performed well on the composite score, showcasing that setting a conservative catch goal is a viable management strategy. For the constant abundance harvest strategy, the highest score was only slightly higher than the baseline of zero-harvest (TC or MAC = 0), thus, this harvest strategy didn't result in greater ecological or fishing benefits than when harvest was never permitted.

In comparison, based on current colonial fisheries policies and values, the constant catch strategies had the highest composite performance, followed by the in-season harvest strategies with a fishing threshold of 4000 (Figure 10B). This composite table upweighted the importance of harvest and downweighed the importance of conservation and abundance. Specifically, constant catch strategies with the lowest TC and the highest TC scored the best. In contrast, no fishing (TC = 0) scored the lowest with a score of 0.50, eliminating this option from the potential management strategies in this fisheries policies scenario. Overall, our result highlights how the weighted values of the performance metrics mostly dictate the highest-scoring management strategies.

**A) Composite trade-off table weighted with HIMRD fisheries policies**

Harvest strategy	TC or MAC	Fishing threshold		
		4000	6000	7500
Constant abundance	0	0.78	0.87	0.92
	500	0.92	0.92	0.93
	1,000	0.72	0.74	0.76
Constant catch	2,000	0.38	0.37	0.37
	3,000	0.27	0.27	0.28
	5,000	0.31	0.31	0.31
	0	0.91	0.91	0.91
In-season	500	0.99	0.99	0.98
	1,000	1.00	1.00	0.99
	2,000	0.86	0.98	1.00
	3,000	0.73	0.89	0.92
	5,000	0.64	0.80	0.87
	0	0.91	0.91	0.91

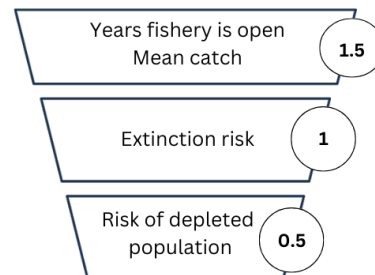
**Performance metrics and their weighted value:**



**B) Composite trade-off table weighted with conventional fisheries policies**

Harvest strategy	TC or MAC	Fishing threshold		
		4000	6000	7500
Constant abundance	0	0.78	0.78	0.73
	500	1.00	1.00	1.00
	1,000	0.94	0.96	0.97
Constant catch	2,000	0.83	0.82	0.83
	3,000	0.83	0.83	0.84
	5,000	1.00	1.00	1.00
	0	0.50	0.50	0.50
In-season	500	0.94	0.88	0.83
	1,000	0.96	0.89	0.84
	2,000	0.94	0.92	0.86
	3,000	0.85	0.91	0.86
	5,000	0.71	0.82	0.84
	0	0.50	0.50	0.50

**Performance metrics and their weighted value:**



**Figure 10. Composite trade-off table of candidate harvest strategies as a function of the harvest control rules based on fisheries policies.**

Defined by either total catch (TC) for constant catch or maximum allowable catch (MAC) for in-season harvest strategy and the fishing threshold (in individuals). To facilitate the interpretation, we normalized the score across all harvest strategies, so the highest score has a value of 1, and all other values scaled accordingly. Shading indicates the percentile value of the corresponding harvest strategy score, with dark colors being the 99<sup>th</sup> percentile. The performance metrics are weighted differently, based on fisheries policies: (a) HIRMD fisheries policies, and (b) conventional fisheries policies (see inverted pyramid on the right).

## 4. Discussion

### 4.1. Overview of key findings

Negotiations to support more equitable agreements between state-led governance and Indigenous Nations are ongoing in fisheries management. In this context, many Indigenous and non-Indigenous scholars, as well as social and fisheries scientists, are calling for institutional changes to decentralize governance systems, including the re-emergence of smaller-scale community-led fisheries (Housty *et al.*, 2014; Atlas *et al.*, 2020; Artelle *et al.*, 2021; Salomon *et al.*, 2023). One key step towards more equitable fisheries in Canada and elsewhere is the indigenization of environmental management approaches. From this perspective, we sought here to rethink the traditional quantitative fisheries management process to make space for multiple perspectives within a complex system.

We developed and applied a value-driven forward simulation centered on Haítzaqv values, knowledges and practices to co-produce knowledge that will serve Haítzaqv community goals for advancing equitable and resilient salmon fisheries. Three key findings emerged from our closed-loop simulation. First, we found clear evidence that an in-season harvest strategy can mitigate some climate risk on the long-term resilience of the Kvai system hísn̓ population. Second, a weighted trade-offs analysis can decrease mismatches between contemporary fishing management and local communities. Third, local monitoring methods allowed for more effective, nuanced quantitative advice for management. As this participatory modelling process is a relatively novel approach for defining management objectives and trade-offs for salmon fisheries in British Columbia, we also discuss here insights learned in the development of this approach.

#### 4.1.1. In-season run timing forecasts improves outcomes under climate change

Of the multiple harvest strategies we tested, our analysis suggests that those including a fishing threshold, especially when paired with an in-season adaptive fishing closure, could promote critical precautionary mechanisms for bolstering climate-resilient fisheries. A fishing threshold delineates the minimum spawner abundance threshold

under which fishing is allowed. We found that constant abundance and the in-season harvest strategies were the most robust to climate-induced changes in marine productivity. During periods of decreased marine productivity, the fishing threshold closure can act as a safety buffer, allowing the population to rebuild to the desired abundance level. In addition, the in-season strategy outperformed the constant abundance strategy across all scenarios and fisheries policies. The main difference between the two is the forecasting method: the constant abundance strategy used a pre-season recruitment forecast based on smolt recruitment output and average marine survival, while the in-season strategy relied on an in-season run timing forecast based on the average timing of adult returning to the weir. Since the onset of the fishing closure depends directly on the forecast, the harvest control strategy can only be as effective as the forecast prediction accuracy.

These harvest scenarios were selected to reflect a key challenge for salmon management. Fisheries resource managers focus on ocean-based commercial salmon fisheries and rely on pre-season forecasts to set the harvest quota for the upcoming year (Atlas *et al.*, 2020). However, despite extensive research on how environmental conditions drive fisheries population dynamics (Crone *et al.*, 2019; Maunder and Thorson, 2019), pre-season forecasts of Pacific salmon recruitment remain challenging (DeFilippo *et al.*, 2021; Wainwright, 2021) as recruitment exhibits unpredictable large temporal variation among years (Maunder and Thorson, 2019). When recruitment forecasts are over-optimistic, they can lead to inflated harvest quotas resulting in overfishing and/or depleted salmon populations in low recruitment years (Haltuch *et al.*, 2019).

In-season run forecasts are more likely to produce reliable recruitment estimates than pre-season forecasts since they utilize the historical cumulative passage estimates to predict the overall annual run (Michielsens and Cave, 2019). In-season forecasts are also ideally suited to traditional Indigenous management systems where salmon is harvested during their homeward migration to their natal river, either in the river, or at the head of an inlet where the river enters the ocean (Haggan *et al.*, 2004; Turner, 2020). Simulation results confirmed that in-season cumulative run forecasts, due to their higher accuracy and more timely feedback to the management system, improved long-term social-ecological outcomes compared to pre-season forecasts, leading to better harvesting decisions for the fishing season. Investing in these type of precautionary

dynamic management approaches, and the local monitoring systems that support them, will thus be critical in an era of rapid and unpredictable climate-driven changes.

#### **4.1.2. Indigenous values matter when scoring harvest strategies**

In fisheries management assessment, the best-performing harvest strategy stems from the trade-offs between operational objectives emerging from the different components of the socio-ecological fisheries system (Punt *et al.*, 2016). Unsurprisingly, the best-performing harvest strategy is highly sensitive to the weight accorded to each operational objective. For instance, the trade-off table adapted to HIRMD's objectives demonstrated how cultural values can directly influence the management options that should be considered by selecting in-season harvest as the superior strategy. By contrast, the composite trade-off table that allocated more weight to economic objectives than biological ones, reflecting a more conventional 'business-as-usual' fisheries perspective, identified the best-performing harvest strategy as constant catch harvest.

A key finding from our study was that a trade-off table prioritizing Indigenous objectives selected a different harvest strategy than the trade-off table representing a more traditional fisheries perspective. However, it can be challenging to communicate this extensive technical modelling processes to decision-makers and rights holders, and to iteratively gather feedback on results and interpretation (Fulton *et al.*, 2014; Punt *et al.*, 2016; Goethel *et al.*, 2019). Research outcomes are inherently biased toward the epistemology of the ones who produce knowledge, as no methodology process is independent of human values or perspectives (Salomon *et al.*, 2023). As such, rights holders should be allowed to lead when using these trade-off analyses to guide future fisheries management decisions, not the analyst.

Additionally, since operational objectives directly arise from conceptual (value-based) objectives and are consequently shaped by worldviews and values, their order of importance should be explicitly incorporated into the trade-off analysis to ensure that local values are accounted for. To alleviate some mismatches between contemporary fishing management and local communities, particularly Indigenous Nations, we argue that a weighted composite table such as the one we designed here, can support a transparent analytical process.

#### **4.1.3. Local monitoring methods to support Indigenous-led governance**

Place-based stewardship rooted in multigenerational knowledge of salmon-driven ecosystem have been disrupted with the colonial dislocation of Indigenous people from their homelands. This erosion has been exacerbated by the reduced monitoring capacity of a centralized governance system, limiting “on the ground” knowledge of fisheries managers (Adams *et al.*, 2021). Nowadays, run timing, abundance numbers and productivity levels for many salmon populations are hypothesized from nearby indicator populations. This lack of local information on salmon population status is a frequent barrier to sustainable fisheries (Atlas *et al.*, 2020). Indeed, the quality of fisheries management advice depends on the available data (Adkison, 2022). The Koeve Salmon Ecosystem Study was created in part to address this information deficit, and the smolt and adult hísñ abundance data collected through their weir program provided valuable insights into a key uncertainty for local management, freshwater vs. marine survival rates. In addition, it allowed us to estimate a bespoke spawner-recruit relationship instead of assuming local Koeve dynamics matched that of other systems. This spawner-recruit relationship was used in the closed-loop simulation study to represent both the mean relationship and the uncertainty in its estimation, ensuring that explorations of optimal harvest strategies in the face of unknown futures were representative of local conditions. Our findings thus highlight the central role of local monitoring projects such as the Koeve salmon ecosystem study in supporting robust management advice.

Beyond improved management advice, place-based stewardship, such as the Koeve salmon ecosystem study, also support Indigenous-led governance. Indeed, local management is an integral component in upholding local values, practices, and ways of knowing. As Mike Reid, one of our Haítzaqv research collaborators, said:

If we can apply local management, that is when we can start applying all the different values, like respect, protecting the river, etc.

A shift towards a polycentric government is necessary to respect local beliefs system (Folke *et al.*, 2005; Salomon *et al.*, 2019; Cumming, 2022). As governance principles are intertwined with place-based stewardships, investing in Indigenous-led monitoring programs can strengthen Indigenous governance structures and legal systems that

predate colonial systems, placing them on more equal footing with federal co-governance partners.

#### **4.1.4. Limitations and biological assumptions**

Our closed-loop simulation evaluated how key uncertainties impact the success of different management strategies in the Kvaí river system. However, as these simulations did not predict short-term trends in Kvaí spawner abundance, as findings are intended to guide longer-term decision-making (Fulton *et al.*, 2014). In addition, we were unable to include a monitoring submodule (Punt *et al.*, 2016) to represent how data are collected from the managed system for logistical reasons. This limited our ability to assess how uncertainty in the collection of spawners and smolt data could have shaped conservation and management outcomes. Ideally, we would have refitted the simulated “observed” data for each year of the simulation to the spawner recruit model to update population dynamics (Punt *et al.*, 2016). Instead, we assumed a stationary spawner recruit relationship throughout the simulation, which could result in a mis-estimation of risk since management regulations are not responsive to new information on the S/R dynamics (but noting we did account for uncertainty around that stationary relationship). Similarly, a lack of data prevented the inclusion of an implementation submodule, so we had to assume that management advice was implemented perfectly (e.g., without errors such as deviations from the prescribed allowable catch). However, the inference drawn from our analysis is likely robust to these simplifying assumptions because we are assessing overall long-term trade-offs, rather than optimizing short-term management strategies.

Informed assumptions about biological processes and associated uncertainties have to be made when simplifying the complex Kvaí socioecological fisheries system into a mathematical model. First, we assumed a stationary Beverton Holt-type relationship between the spawners and the juvenile recruits throughout, as it is commonly assumed to be the best model to represent the spawner-juvenile recruit dynamics in salmon (Hilborn and Walters, 1992; Adkison, 2022). The stationary assumption is appropriate in the context of a data-limited fisheries system as there are not enough data to inform a non-stationary relationship. Instead, we accounted for future productivity changes through different marine survival scenarios and temporally-autocorrelated uncertainty. Secondly, we assumed a constant rate of 5 % of the Kvaí

hísn might be intercepted by commercial mixed-stock fisheries. However, due to a lack of high-resolution genetic sampling in marine fisheries around BC and Alaska (The Pacific Salmon Commission, 2023), we do not currently know the number of individuals that are harvested before reaching Hałtzaqv territory. We chose 5 % based on first-hand knowledge on the commercial salmon fisheries across the Northern Boundary Area and Central Coast of BC (W. Atlas *pers. comm.*).

## **4.2. Rethinking fisheries quantitative assessment: lessons learned**

Due to the Indigenous resurgence and decolonization movements seen across North America in recent decades, it is now well-documented that resource management has a deeply colonial and capitalist history (Berkes, 2003; Reid *et al.*, 2021) that still influences how science is conducted. For fisheries management, one crucial step towards authentic reconciliation is to acknowledge that quantitative models (e.g., stock assessments) have often been used as colonial tools to dispossess Indigenous people of their inherent rights to govern their own fishery resources (Newell, 1993; Harris, 2017). Quantitative models always have an inherently subjective component as the analytical choices made by quantitative scientists and government biologists represent the belief system and research paradigms of the institution in place (Adams *et al.*, 2014; Punt *et al.*, 2016; Silver *et al.*, 2022). One such example is the by-default historical definition of management objectives for single species based on the objective of maximizing yield, rather than maintaining higher biomass or balance across interconnected ecosystem components. These intangible aspects, such as unrecognized or unacknowledged assumptions that form the basis of model structures, of quantitative management, can take an insidious form as often Western scientific approaches are implicitly deemed to be objective and free- from value-driven bias (Reid *et al.*, 2014; Atlas *et al.*, 2020; Salomon *et al.*, 2023).

The failure to acknowledge the presence of subjectivity in contemporary fisheries management approaches can have tangible consequences on management outcomes (Artelle *et al.*, 2019, 2021; Salomon *et al.*, 2019; Silver *et al.*, 2022) from narrowing the scope of possible management policies to disrupting locally adapted management cultures by dismissing the governance systems of Indigenous communities (Salomon *et al.*, 2019). Here, we discuss insights learned throughout the process of co-

producing knowledge for the Koeye hísn fisheries with the hope of assisting future researchers that might wish to undertake similar projects.

#### **4.2.1. Importance of values-driven simulation in informing resource management**

Our value-driven forward simulations of K'vaí hísn population provide useful insights for aligning the management of K'vaí FSC fisheries with the stated objectives of the Haítzaqv Nation. For instance, to align with precautionary management practices as advised by HIRMD, we chose fishing threshold with spawner abundance equal to or higher than  $S_{msy}$ . In contrast, most contemporary fishing practices aim for salmon population abundance to be at or below  $S_{msy}$ . As a result of our more precautionary spawner abundance objective, we found that fishing mortality (such as total catch or maximum allowable catch) influenced the overall performance of a harvest strategy more than the fishing threshold across all simulations.

Aiming for spawner abundance at or below  $S_{msy}$  reflects a long-standing belief in Eurocentric fisheries approaches that population abundance exceeding  $S_{msy}$  are undesirable as they will result in over-compensatory recruitment dynamics, reduced yields, and potentially forgone harvest (Langdon, 2015). This assumption stems from a utilitarian perceptive that prioritizes human needs and economic objectives (such as total catch), in opposition to a relational–reciprocity perceptive in which providing salmon for other-than-human species is equally paramount (Artelle *et al.*, 2021). This philosophy is shared by many Indigenous communities, including the Haítzaqv Nation, and is reflected in their stewardship of the land (Housty *et al.*, 2014). Such differences in management objectives between aiming for or exceeding  $S_{msy}$  highlight how the use of default parameter settings from conventional fisheries management might fail to align with Indigenous values and needs. Values-driven simulations co-developed with Indigenous communities are thus more likely to result in fisheries management strategies that uphold local values, management objectives, and governance practices.

#### **4.2.2. Decolonizing linguistic terminology in quantitative fisheries**

Throughout this project, we learned a valuable lesson; words too are associated with value-belief systems, and thus, can perpetuate colonial inequalities (Berkes, 2003).

The linkage between colonialism and terminology (language choices) becomes more obvious when considering the importance language holds within a cultural context (Meighan, 2022). Often, Indigenous languages describe patterns of seasons, cultural places, and spiritual values. Many Indigenous governance principles, such as the Ǿvǿlǿs - Heiltsuk Laws (laws of the ancestors), do not have an appropriate equivalent in the English language (Kovach, 2009). These local concepts evolved through time to represent cultural and context-specific kinship relationships between Indigenous people and their homeland (Biin *et al.*, 2021; Chiblow and Meighan, 2022). When we use English to discuss fisheries management, the most common (sometimes seemingly innocuous) terms can often represent a utilitarian-centred worldview, missing the larger relationships between Indigenous peoples and their homelands. For instance, the word “*resource*” can be problematic in an Indigenous context, as it is associated with the history of exploitation of people as well as ecosystems that resulted in commodifying and marketizing Indigenous homelands (Berkes, 2003).

We must improve our terminology to challenge the status quo and create much-needed institutional change, including in fisheries management. Different pathways forward have been previously defined by Indigenous scholars, either to completely stop the use of problematic terms (Cornthassel, 2012), or to redefine their meanings to include a more holistic definition (Reid *et al.*, 2020). When writing this thesis and working with the Haíłzaqv community, we were mindful to examine and rethink what conventional fisheries management terms represented and implied. We tried as much as possible to avoid terms associated with a utilitarian and colonial worldview. For instance, instead of using “*escapement goal*” a term commonly used in fisheries to describe conservation goal and that directly means “fish that escaped the commercial fishery industry”, we used “abundance target”. As another example, we preferred employing the term “population” as an alternative to “stock”, which refers to fish solely as an extractive resource. We also tried, when possible, to use Heiltsuk words, to illustrate how the Ǿvǿlǿs, responsibilities, and connections to the land is embedded within the Heiltsuk language. By honouring the relational connection of language and place, researchers, including fisheries scientists, can be part of a process of self-decolonization enabling a plurality of perceptions and ways of describing and understanding complex fisheries system, such as the Koeve social-ecological system.

### 4.3. Conclusion

Western worldviews are still too often imposed on Indigenous nations in the management their lands, fisheries and waters (Belcourt et al., 2015; Reid et al., 2021; Silver et al., 2022). This project is one contribution amongst many aiming to support Indigenous Nations in reclaiming their inherent rights to manage their relationships with the land and sea following their governance principles and management objectives.

We approached quantitative modeling using a value-driven forward simulation approach, a novelty in the quantitative modelling realm. We found here that pre-season forecasting systems developed for commercial salmon fisheries result in elevated risks of overfishing and depleted populations, especially under climate change; that local monitoring improves the likelihood of success of fisheries management and the local relevance of modelling exercises; and that different harvest strategies are selected when Indigenous values are prioritized. More generally, we showed that value-driven models co-developed with Indigenous communities within a socially and culturally appropriate framework can be a practical way to create space for multiple ways of knowing, leading to more ecological and socially just outcomes.

Finally, implementations of values-driven simulations such as ours should not be developed once and repeated unchanged through time, but instead be part of a dynamic co-production process, evolving as new information on the Kvaí social-ecological system arises or as community objectives change.

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## Appendix A.

### Prior distribution tables

**Table A.1. Prior distributions for model parameters of the Beverton-Holt spawner-recruit model**

Symbol	STAN	Prior
$\sigma_R$	sigma	$\sigma_R \sim \text{Cauchy}(0,1)$
$\beta$	beta	$\beta \sim \text{Normal}(2.80000 \times 10^5, 1.4 \times 10^5)$
$\ln(\alpha)$	log_alpha	$\ln(\alpha) \sim \text{Normal}(3,1)$
	smolt	$\text{Lognormal}(\ln(\text{mean\_smolt}_{yi}), \sigma_R)$
	smolt_missing	$\text{smolt\_miss} \sim \text{Normal}(5 \times 10^4, 1 \times 10^4)$

**Table. A.2. Prior distributions for model parameters of the cumulative run timing model**

Symbol	BRMS	Prior
$\varpi$	b_Intercept	$\varpi \sim \text{Normal}(0,10)$
$\varphi$	b_stan_day	$\varphi \sim \text{Normal}(0,10)$

## Appendix B.

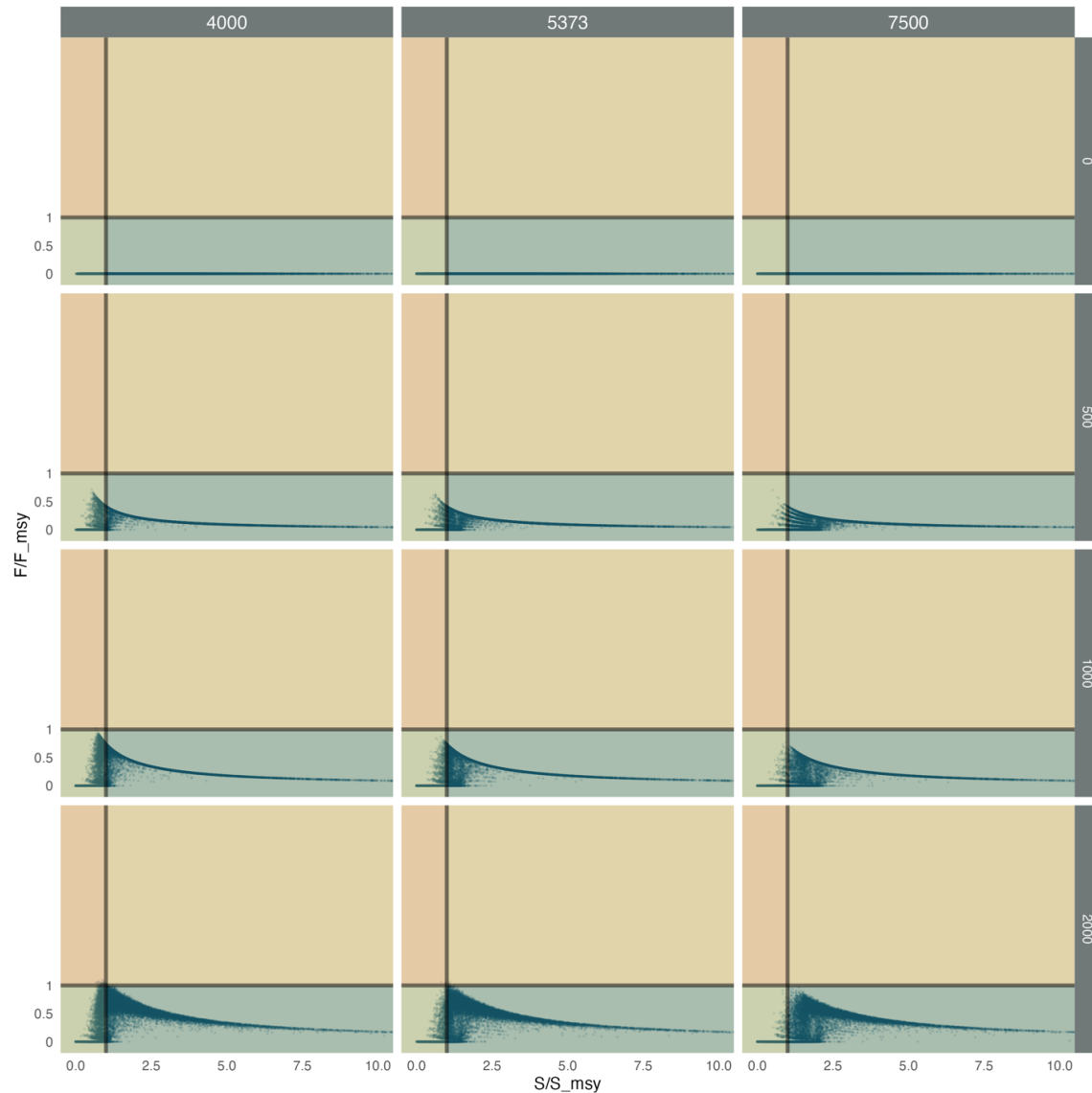
### Sensitivity analysis to in-season harvest decisions

We explore different in-season harvest decision that could be applicable for the fisheries management at the Kvaí. I particularly wanted to know if the harvest decision model impacted the total catch, and if we would have higher “forego” harvest between daily vs weekly.

#### Daily harvest decision

We randomly select 10 days between Calendar day 167 (June 16 ) and Calendar day 208 (July 27) to represent harvest days. Those days can be changed, but since few cumulative fish have passed the weir very early in the season, the in-season forecast doesn't predict the run well. It most likely will overestimate the total run. I don't recommend using dates from the first two weeks of the run to avoid overfishing.

Harvest happens on that randomly selected day if the forecasted run of the Calendar day (  $\widehat{N}_d$  ) is higher than the fishing threshold. There is a fixed maximum of fish that can be caught daily. I try different numbers to see which numbers makes to most sense. Right now, it is a daily max of 100 fish for total of 500, daily max of 200 for total of 1000 etc etc. This fixed daily maximum number of fish changed according to the overall maximum number of fish allowed. It helps spread the harvest throughout the season (and protects genetic diversity etc.). Once the total harvested fish reach the maximum annual harvest, the harvest stops for the rest of the season.



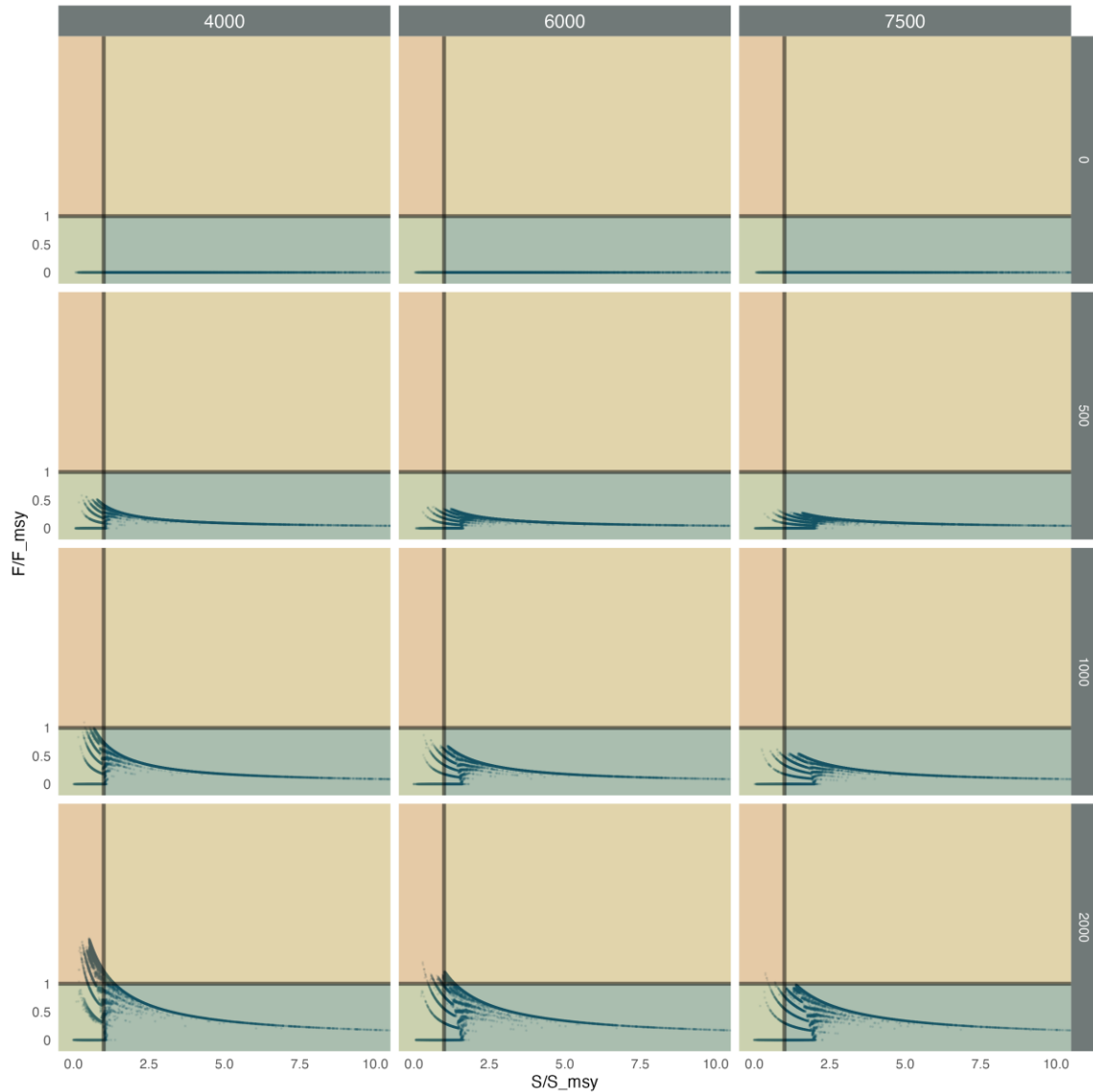
**Figure B.1. Population status for the daily harvest decision;**

(1) unsustainable: population is depleted and overfishing is occurring (red), (2) population is above  $S_{msy}$  but overfishing is occurring (orange), (3) population is depleted, but fishing allows population to grow (green), (4) sustainable population, fishing allows population to grow (blue). Each dot represent a year in a simulation, and every Monte-Carlo simulation is shown. We showed the simulated years from year 25th to year 75th for all Monte Carlo trials, so each point is one individual year.

## Weekly harvest decision with a maximum allowable catch

Each Monday from week starting June 16<sup>th</sup> to the end of the season, there is a harvest decision. Harvest happens for the week if the forecasted run of the Calendar day ( $\widehat{N}_d$ ) is higher than the fishing threshold. A fixed maximum of fish can be caught weekly to help spread the harvest throughout the season (and protect genetic diversity

etc.). The weekly maximum harvest change according to the annual harvest target (e.g.: for an annual harvest target of 2000 fish, the weekly max is 350).

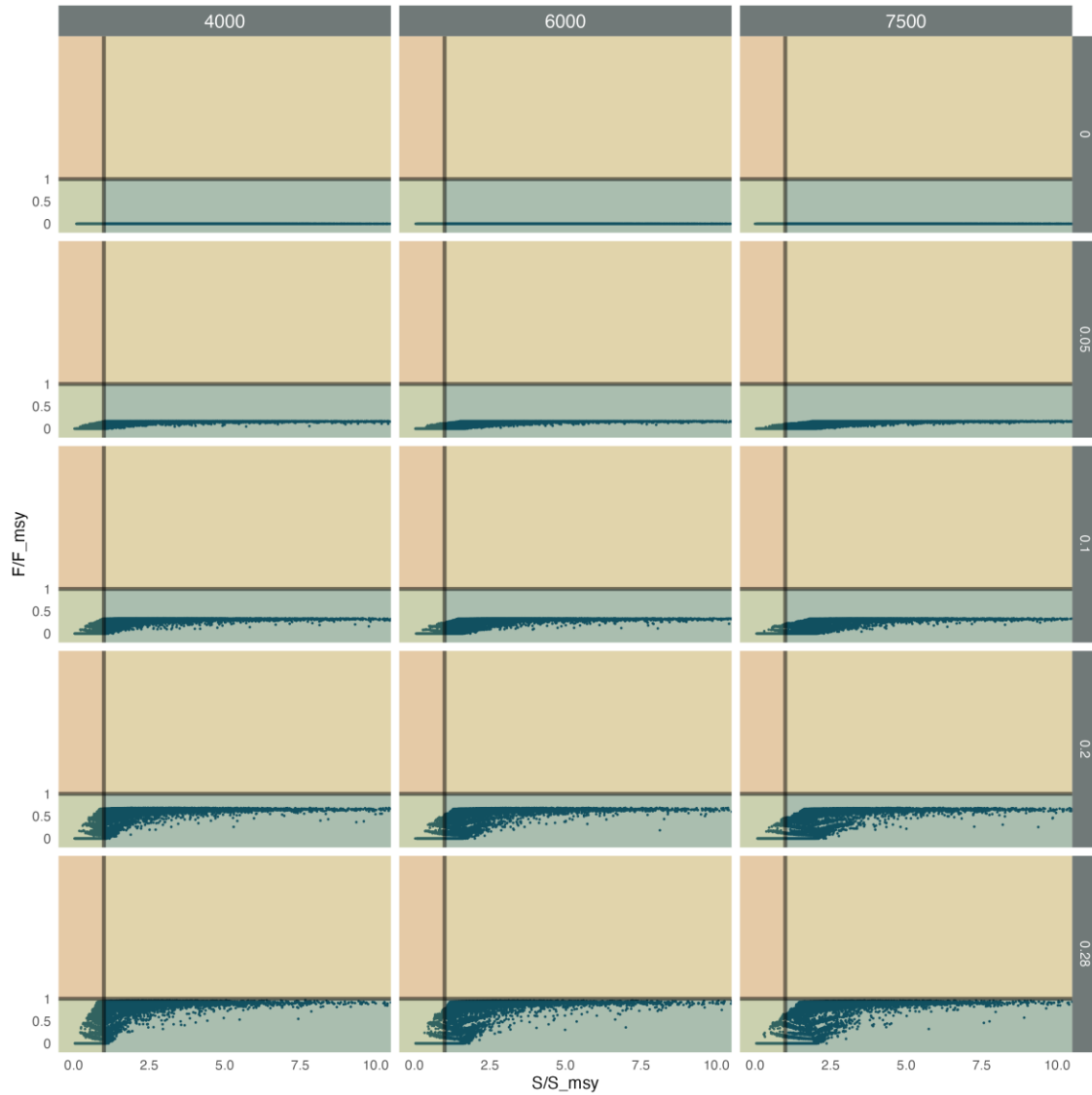


**Figure B. 2. Population status for the weekly harvest catch decision;**

(1) unsustainable: population is depleted and overfishing is occurring (red), (2) population is above  $S_{msy}$  but overfishing is occurring (orange), (3) population is depleted, but fishing allows population to grow (green), (4) sustainable population, fishing allows population to grow (blue). Each dot represent a year in a simulation, and every Monte-Carlo simulation is shown. We showed the simulated years from year 25th to year 75th for all Monte Carlo trials, so each point is one individual year.

## Weekly harvest decision with a harvest rate

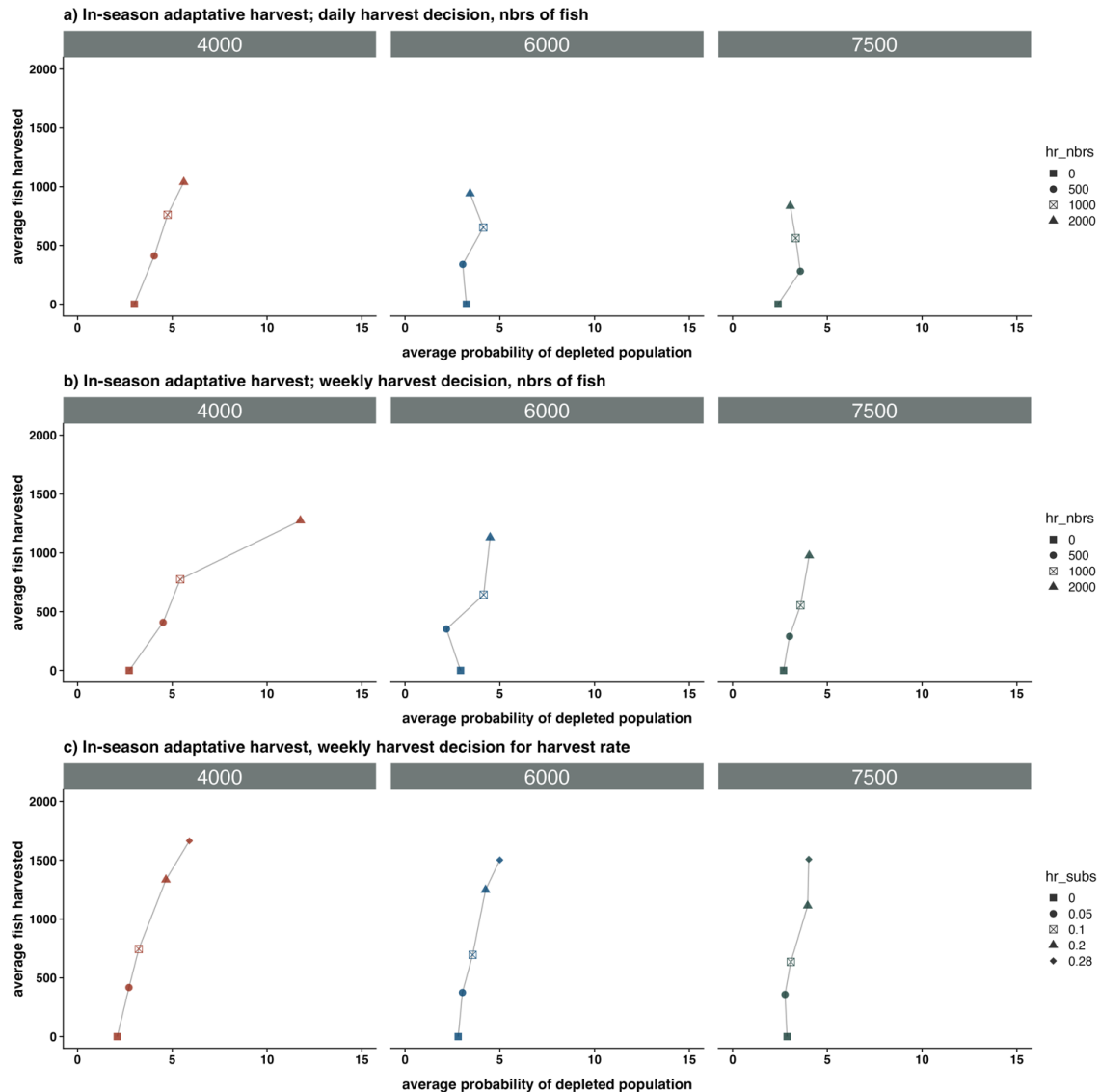
Each Monday, from June 16<sup>th</sup> to the end of season, there is an harvest decision. Harvest happens for the week if the forecasted run of the Calendar day ( $\widehat{N}_d$ ) is higher than the fishing threshold. This one is pretty simple; it has the same harvest rate throughout the season. The optimum harvest rate for MSY is 0.28



**Figure B.3. Population status for the weekly harvest rate decision;**

(1) unsustainable: population is depleted and overfishing is occurring (red), (2) population is above  $S_{msy}$  but overfishing is occurring (orange), (3) population is depleted, but fishing allows population to grow (green), (4) sustainable population, fishing allows population to grow (blue). Each dot represent a year in a simulation, and every Monte-Carlo simulation is shown. We showed the simulated years from year 25th to year 75th for all Monte Carlo trials, so each point is one individual year.

## Comparison between the alternative in-season harvest decision

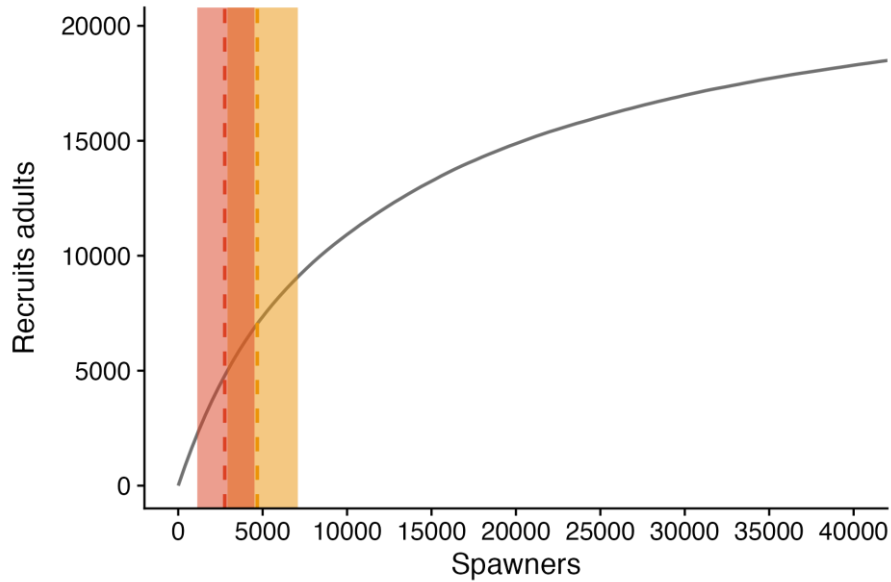


**Figure B.4. Trade-offs between mean catch and the average probability of depleted population ( $S < S_{msy}$ ) among in-season adaptive harvest strategies.**

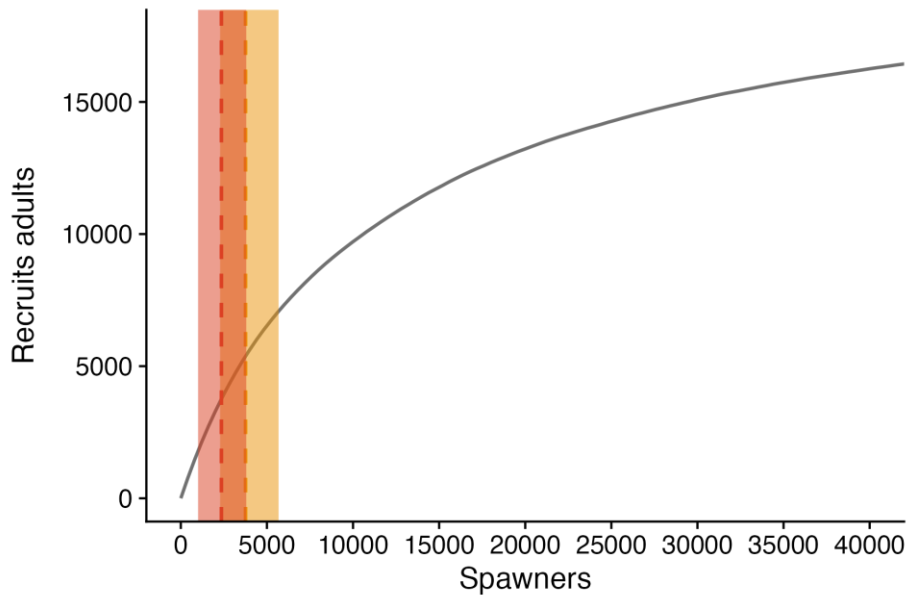
A) daily catch harvest decision as a function of a total catch number ranging from 0 to 2000. B) weekly catch harvest decision as a function of a total catch number ranging from 0 to 2000. C) weekly harvest rate harvest decision as a function harvest rate ranging from 0 to 0.28.. Predicted average catch was measure as the total mean of each Monte-Carlo trial's catch average (500 in total). Average probability of depleted population as the mean proportion of the last 25 years of the simulation for each Monte Carlo trial that was below  $S_{msy}$ . Contrasting strategies between and among panels shows trade-offs between conservation and catch. This figure only show the marine survival scenario of 30 %.

## Appendix C.

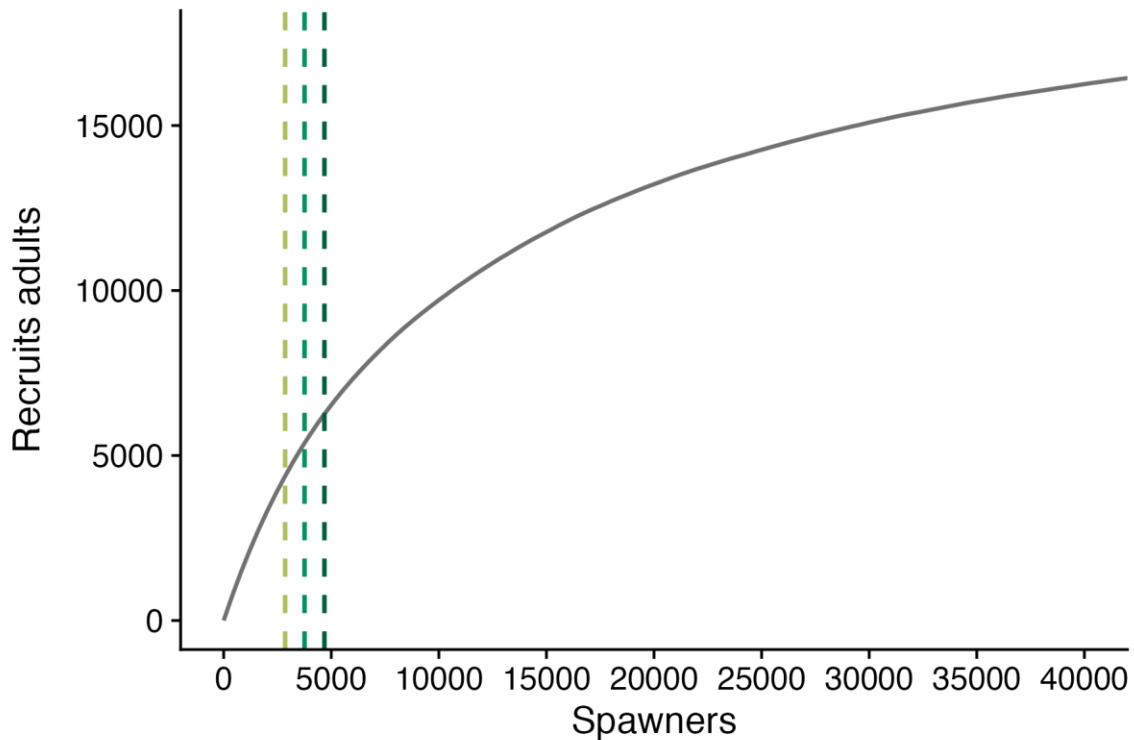
### Reference points and climate-change scenarios



**Figure C. 1.** 95% credible intervals of the  $S_{gen}$ (red) and  $S_{msy}$ (orange) based on the posterior distributions of the SR stan model for a smolt-to-adult survival of 9 %



**Figure C. 2.** 95% credible intervals of the  $S_{gen}$ (red) and  $S_{msy}$ (orange) based on the posterior distributions of the SR stan model for a smolt-to-adult survival of 8 %

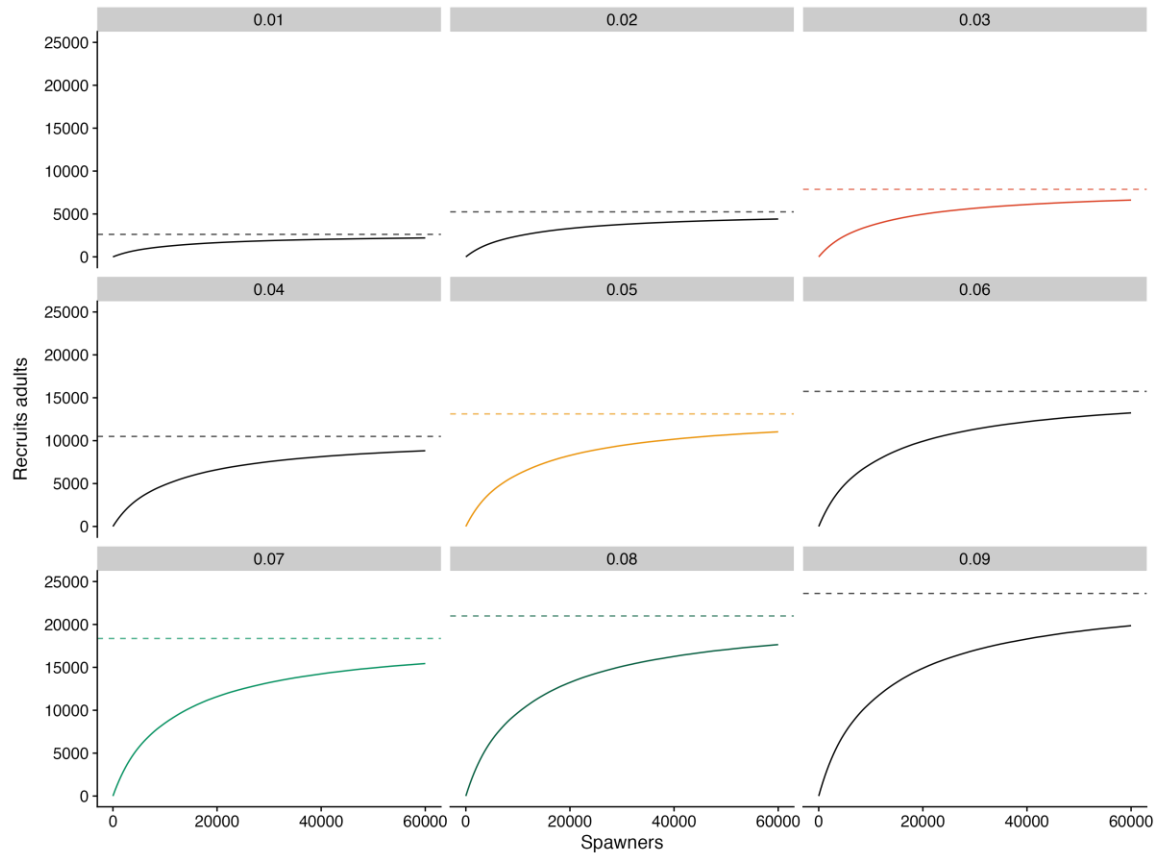


**Figure C. 3. Spawner at maximum sustainable yield as a function of smolt-to-adult survival. Pale green is 7 %, Medium green is 8 %, dark green is 9 %**

## Climate-change scenarios

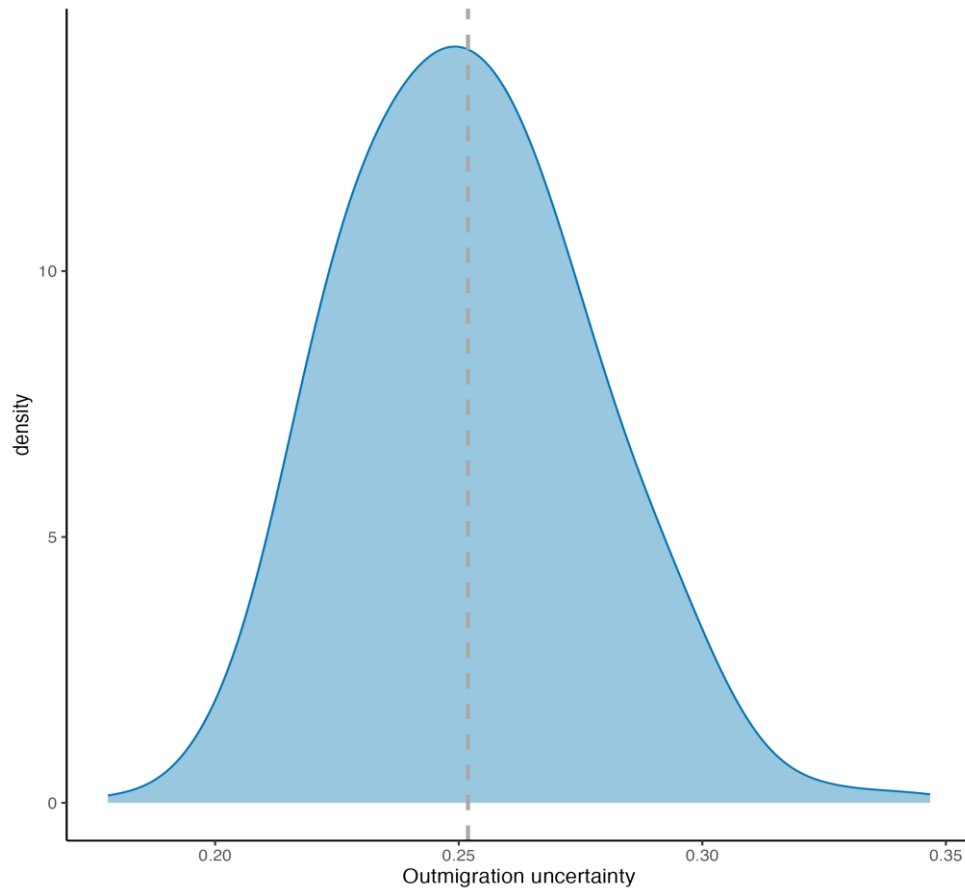
Since little is known about marine survival in the ocean for Pacific salmon, we had to make "best guesses". To represent the smolt to adult survival rate more accurately and allow for more stochastic variation in the closed-loop, we separated outmigration from marine survival. The book did a meta-analysis for hísñ for outmigration survival as 0.25 % survival (Quinn, 2018).

Based on the hísñ data from the weir, we know that smolt-to-adult is currently 7.5 %, so we chose with HIRMD looking at marine survival of 35 %, 30 %, 25 %, and catastrophic 15 % for respective smolt\_to\_adult survival of 8.7 %, 7.5 %, 6.2 % and 3.5 %

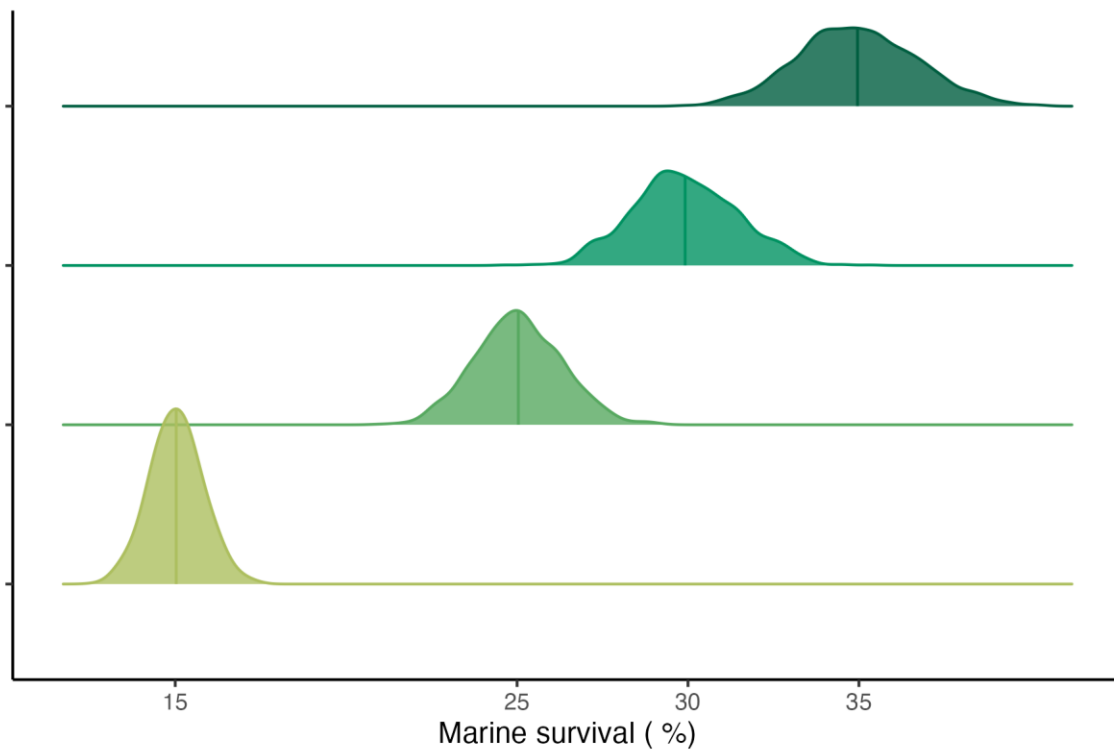


**Figure C. 4.** Maximum carrying capacity of the system as a function of smolt-to-adult survival rate, with smolt\_to\_adult survival ranging from 0.01 to 0.09. The horizontal line shows maximum capacity of the equilibrium system. The colors are associated with the climate change scenario we explored.

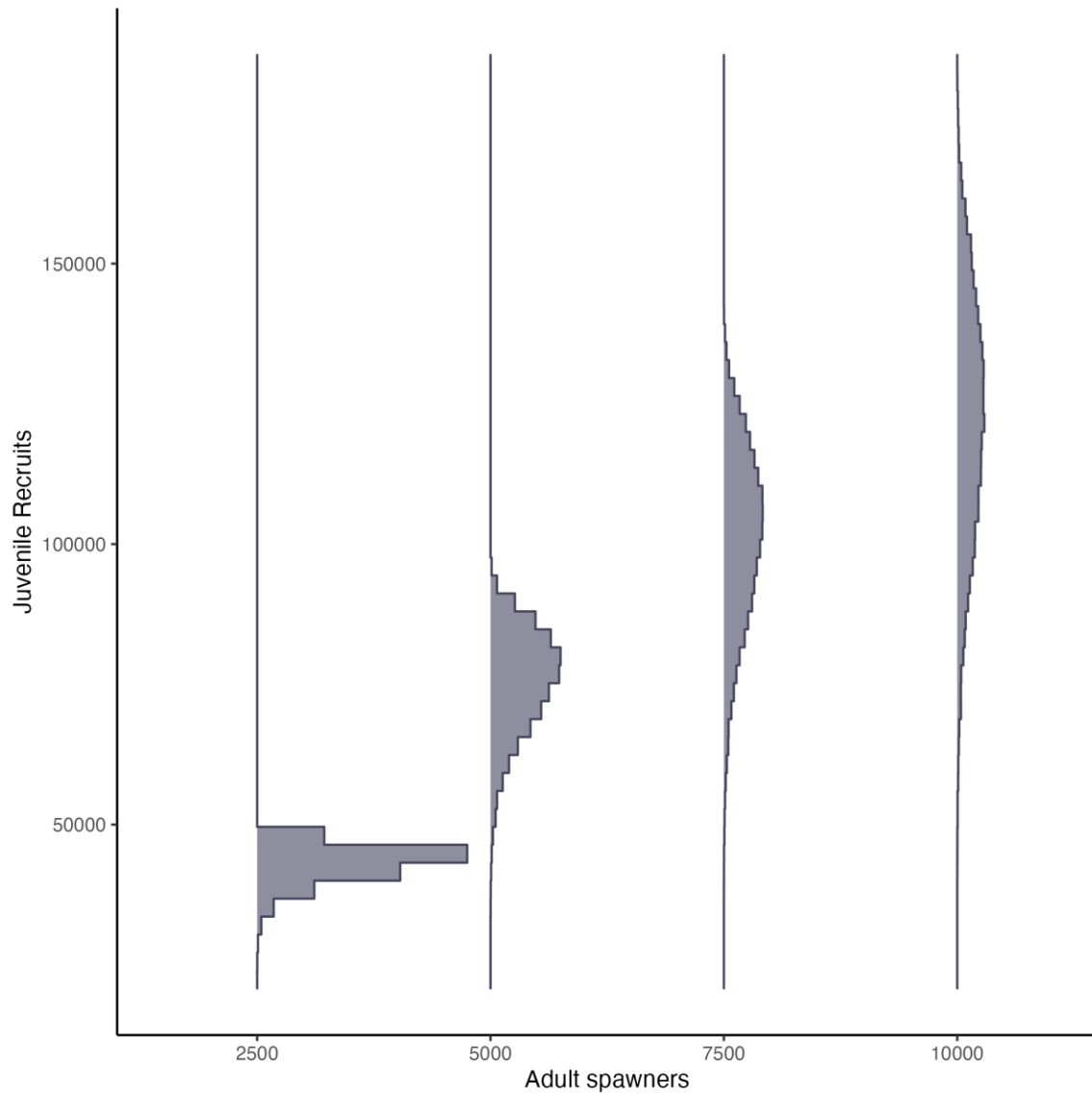
## Appendix D. Uncertainties generated in the closed-loop simulation



**Figure D. 1.** Lognormal distribution of the outmigration rate, with a mean of 0.25 and a standard deviation of 0.10



**Figure D. 2. Marine survival rate lognormal distribution as a function of the mean marine survival associated with climate-change scenarios, with mean of 15 % (catastrophic scenario), 25 % (low marine survival), 30 % (baseline scenario), and 35 % (optimistic scenario). All scenarios have a standard deviation of 0.05.**



**Figure D. 3. Recruitment variation around the mean recruitment rate of the spawner-recruit Beverton-Holt model, following a lognormal distribution.**

## Appendix E.

### Conversation Guideline for K'vaí Fisheries

**Broad goals** for the interview:

- Identification of HIRMD vision for future management of K'vaí Hísn salmon:
  - Management objectives for K'vaí fisheries
  - Performance metrics
  - Potential management options to explore in the model
- Management objectives for K'vaí fisheries:
  1. What is the state of Hísn populations now in the Haítzaqv territory compared to what they were in the past? Could you specify what is the time period (regime shift specific to salmon) you are referring to?
  2. What aspects of the current salmon fisheries management are working or aligned with Haítzaqv values and *Gvi'ilas* customary laws and principles? Could you give specific examples?
  3. Which aspects are not working and need to change in the current salmon fisheries management in the Haítzaqv territory to better reflects *Gvi'ilas* customary laws and principles?
  4. What changes in the current system of fisheries management could better support food sovereignty for Haítzaqv Nation?
    - Sub-question: What is food sovereignty for salmon means for you?
  5. What is your vision for future management of Hísn at K'vaí? Ideally, what would be the role of K'vaí fishery for the Haítzaqv Nation?
    - What about economy objectives?
    - What about ecology/ conservation objectives?
    - What about cultural objectives?
    - Is there any other category that we should include?
  6. How should salmon be managed at K'vaí to reflect the *Gvi'ilas* principles and customary laws?
  7. On what time frame should we be thinking about management objectives for K'vaí Hísn FSC fishery?
  8. What objectives would be important to try to achieve regarding fisheries management in the short-term vs long term?

- Management scenarios for Kvaí to inform simulations
  1. What different types of harvest strategies would be important to consider in the model?
  2. What would be the exploitation rates that you would like to see represented in the model?
  3. Do you want to explore different scenarios in term of monitoring intensity?
  4. Are there key drivers of change of Kvaí Hísn populations (now and the future) that you would like to see represented in the model?
  5. In term of risks associated with models, what are the levels of uncertainty that you are not comfortable with?
  6. What should we take into consideration when measuring the benefits or drawbacks of a particular simulation scenario?
- Performance metrics or indicators of success/failures based on the objectives described above
  1. For each objective mentioned above, can you give specific indicators that would indicate that Kvaí FSC fishery is successful vs not successful in supporting the Haítzaqv community?

Examples of specific questions I could ask based on their objectives...

- What would be the range for catch of FSC Hísn for the entire season that would be consider best? Acceptable? Worst ?
  - What would be a catch per unit effort that would be best? Worst?
  - How could we maintain stock integrity and genetic diversity?
  - Could you indicate the range of escapement that would be considered best? Worst?
  - What would be the ideal level of participation from the community in this fishery?
2. What are the different ways we can measure success or failure?