Fish–People–Place: Interweaving Knowledges to Elucidate Pacific Salmon Fate

by

Andrea J. Reid

B.Sc., McGill University, 2010
M.Sc., McGill University, 2013

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"*The land knows you, even when you are lost.*"

–(Kimmerer 2013 pg. 36)

Dedication

"I know nothing
of great mysteries
know less of creation
I do know
that the farther backward
in time that I travel
the more grandmothers
and the farther forward
the more grandchildren
I am obligated to both."
–(Maracle 1996 pg. 8)

This dissertation is dedicated to all of those that I share an obligation to, especially my Gigi (Nisga'a for grandmother) Phyllis Stella Stewart who was taken as a child from Gingolx in the Nass River Valley of British Columbia to the Coqualeetza Industrial Institute (residential school) over 500 miles away as the crow flies. She was told to go home once she *"could read, write her name and do arithmetic"* (Stewart 2015). My antithetical experience with education is owed in large part to the Nisga'a Nation who has supported my post-secondary studies from the very beginning, from a time before I had even found my own way home to the Nass River Valley.

Abstract

Migratory organisms carry high ecological and cultural significance as their cyclic movements through time and space create influxes of nutrients into ecosystems and provide important sources of food to people – imprinting on cultures, bodies of practice and management as well as knowledge systems. However, their often long-distance movements between habitats expose them to multiple and potentially interacting risks. Migratory Pacific salmon (*Oncorhynchus* spp.) are threatened by a suite of stressors, both known (*e.g.*, overfishing, climate change) and unknown, that jeopardize their wellbeing as well as that of linked social-ecological systems. A central focus of this thesis is to elucidate the ultimate fate (*i.e.,* survival to spawning grounds) of salmon who[1] encounter fishing gears but either escape or are released as bycatch, and how this fate is shaped by other factors at play (such as rising temperatures). To gain an improved understanding of what other potential factors may be, a second focus here is to identify leading threats endangering salmon and aquatic ecosystems more generally. Different ways of knowing are valued and interwoven in this work, motivated by the Mi'kmaw conceptual framework of *Etuaptmumk* or "Two-Eyed Seeing" which creates a pathway for learning from both Indigenous and Western sciences, using their distinct strengths and methodologies in tandem. Experimental fisheries approaches, carried out in partnership with local and Indigenous fishers and fisheries managers, reveal that the context of salmon capture significantly

[1] 'Who' is a relative pronoun used to introduce a clause giving further information about a person; given the positioning of salmon as relatives in the works described in this dissertation, 'who' is appropriately used throughout to reflect this ecological understanding and awareness (Brown 2017). This follows in the footsteps of literary giants from Herman Melville (Moby Dick) to Shakespeare (Julius Caesar) as well as ground-breaking scientists such as Dr. Jane Goodall (In the Shadow of Man).

influences upstream survival, with the severity of the capture experience, the damage incurred to fish in the process and surrounding environmental conditions (such as water temperature) each being predictive of fate. Two expert threat assessments involving international freshwater scientists and Indigenous knowledge holders, respectively, identified multiple shared concerns (*e.g.*, climate change, infectious diseases, habitat loss, hydroelectric projects) and numerous place-based stressors of local significance for wild salmon populations. Each assessment revealed a profound change in the state of freshwater biodiversity and Pacific salmon harvests over time, respectively, with both declining by an average of 83% between ~1970 and present – signaling the urgency of conservation actions that protect fresh waters, their inhabitants and all that they underpin for people and place.

Acknowledgements

Throughout my doctoral studies, I have been surrounded by concentric circles of support. T'ooyak̲siy' nisim' (thank you all) to the communities and members of the Katzie, Nat'oot'ten, Peters, Stó:lō, Secwépemc, St'át'imc, Tŝilhqot'in, Ts'msyen and xʷməθkʷəy̓əm Nations who welcomed me to their territories and shared with me their love of wild salmon and healthy rivers. I am forever grateful to the Nisg̲a'a Nation, communities, citizens and knowledge keepers who have so warmly welcomed me home to the Nass River Valley. My gratitude also goes to the fish and Lisims (Nass River) who are at the very heart of it all.

The Nisg̲a'a Nation has played a central role in supporting me throughout my studies, and I express my thanks both to them and the Gingolx Village Government's Education Department, especially Renee Garner who encouraged me at every turn and spawned the idea for our annual salmon science camps that have been a highlight of my PhD. I also thank the other major funding sources who have made significant investments in me as an early career scientist, including Carleton University, Indspire, the New Relationship Trust Foundation, the National Indian Brotherhood (NIB) Trust Foundation, the Natural Sciences and Engineering Research Council of Canada (NSERC), the Ontario Graduate Scholarship Program and the Philanthropic Education Organization (details in **Appendix A**). My research on the ground / in the water would not have been possible without funding and in-kind support from NSERC, the Canadian Fishing Company, the Pacific Salmon Commission, the Ocean Tracking Network, Genome British Columbia, the Royal Canadian Geographical Society, the NIB Trust Foundation and the Nisg̲a'a Fisheries and Wildlife Department of the Nisg̲a'a Nation.

I have so enjoyed teaching and learning from Nisg̱a'a youth who have made the salmon science camps all that they are, and designing and instructing my very first course (*"Indigenous Knowledge & the Environment"*; syllabus in **Appendix B**) was one of the most formative experiences of my early career. I thank those Carleton undergraduate students for their creativity and the care with which they considered new and challenging concepts. Thanks also to all those who took time to come speak with my class, especially Dr. Kahente Horn-Miller, Dr. Rebekah Ingram, Suzanne Keeptwo, Dr. Karen Lawford, Dr. Janet Tamalik McGrath, and Pitseolak Pfeifer who I hope to know for a lifetime.

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Life in the field and lab would not have been the same without the UBC/Carleton Sockeye Tagging Project team in 2016 – Katrina Cook, Taylor Wale, Collin Middleton, Art Bass, Christine Stevenson, Laura Elmer, Jacqueline Chapman, David Patterson, Kendra Robinson, John-Francis Lane and field-logistics mastermind Andrew Lotto! Many of these folks also played key roles during our 2017 Fraser sockeye escape research. Thanks for this field/lab season also go to David Moulton, Adam Kanigan, Amy Teffer and the entire Pacific Salmon Ecology and Conservation Lab who came out fishing. I am also grateful to past and present Fish Ecology and Conservation Physiology labmates Shannon Bower, Jill Brooks, Vivian Nguyen, Petra Szekeres and many more for making the between field season time periods so wonderful. Special thanks to my "little big brother" Quinn Stewart for putting up with dusty drives, steep hikes and heavy equipment hauling through the woods each summer, and to his mom Roberta for being my go-to B&B when I'm in the Nass. Launching the not-for-profit Riparia was a significant milestone during my PhD and I am grateful to have friends like Riparia co-founders Dr. Dalal Hanna and Mikayla Wujec who are the best lifelong labmates / travel companions / dive buddies or canoe sharers anyone could ask for. Thanks also to Lauren Eckert, to whom I could speak with until I lose my voice, oh wait, that happens... every time! So many other friends have helped get me through these years from afar – Lesley, Mojeanne, Alexandra, Jeremie, Emma, Madeline, Jessie, John – I love you all! I am so grateful to my family – Mom, Ron, Dad, Linda, Paul, Kate, Charlie Mae (and future baby), Chris, Felicity, Clarence, Clyde, and the entire Lane crew, I couldn't have done this without you. John-Francis, these past five years have bounced us around coast to coast doing all the things we love most, and I am so grateful to have you in my corner and as a co-adventurer for life.

Preface

I would like to acknowledge that this dissertation was prepared from the unceded, unsurrendered territory of the Algonquin Anishnaabeg people (Ottawa). It describes concepts with origins from Indigenous territories around the world and details field research that was conducted collaboratively with First Nations communities spanning British Columbia's three largest salmon-producing river systems – the Fraser, Skeena and Nass Rivers. This includes nations from the xʷməθkʷəy̓əm (Musqueam) at the mouth of the Fraser River in present-day Vancouver, up to my nation's territory – the Nisg̱a'a Nation – the "people of the Nass River" on the British Columbia/Alaska border. Having grown up on Canada's East Coast in Mi'kma'ki, on Abegweit (Prince Edward Island), I was raised apart from Nisg̱a'a culture, language and ceremony and am only finding my way back now through the research processes described in these pages. Living my life off-reserve and as a "white coded" individual, my experience in academia is wholly distinct from that of many Indigenous peoples in higher education in this country. My ambition as an Indigenous fisheries scientist who has benefitted from privileges known and unknown is to create space for Indigenous voices, values, experiences and knowledges in systems and institutions from which they have long been excluded, overlooked or 'othered'. Upon completion of this degree, I will be transitioning to a faculty position (assistant professor) with the University of British Columbia's Institute for the Oceans and Fisheries where I will lead the new Indigenous Fisheries Research Unit and continue to create this space for the next generations of Indigenous fisheries scientists and fish/water/land protectors.

Thesis Format and Contributions

This thesis is comprised of a series of co-authored manuscripts that are in various stages of publication with peer-reviewed journals or are in preparation for submission to such. Given the nature of the collaborative work that I undertake, co-authorship invitations were (or will be) extended to colleagues and partners in research who made substantial contributions to project conceptualization and/or data acquisition and analysis. All co-authors have provided (or will provide) critical input on manuscript drafts and final approvals before publication. Repetition of specific elements (*e.g.*, definitions, methods) is necessary so that each chapter can be a standalone entity, and slight variation in formatting appears across chapters to meet specific journal formatting guidelines. For all collaborative elements of this thesis (**Chapter 2–6**), the pronoun "we" is used throughout the writing to reflect the true collaborative nature of the work at hand. Details of contributions follow:

[2] **Reid AJ**, Carlson AK, Creed IF, Eliason EJ, Gell PA, Johnson PTJ, Kidd KA, MacCormack TJ, Olden JD, Ormerod SJ, Smol JP, Taylor WW, Tockner K, Vermaire JC, Dudgeon D, Cooke SJ. 2019. Emerging threats and persistent conservation challenges for freshwater biodiversity. Biological Reviews. 94:849–873.

This paper was conceptualized by Reid and Cooke, with important guidance from all co-authors from the outset. Reid led manuscript preparation with contributions from all co-authors in their respective areas of expertise. Since its 2019 publication, this article has been cited 250+ times and gained significant social and public media attention (some examples in **Appendix D**; ranks in the top 5% of all research outputs scored by Altmetric).

[3] **Reid AJ**, Eckert LE, Lane JF, Young N, Hinch SG, Darimont CT, Cooke SJ, Ban NC, Marshall A. In Press. "Two-Eyed Seeing": An Indigenous framework to transform fisheries research and management. Fish and Fisheries.

Reid developed the idea for this paper, and all co-authors contributed significantly to conceptual development, most notably Mi'kmaw Elder Dr. Albert Marshall who brought forward the concept of *Etuaptmumk* or "Two-Eyed Seeing" into the academic literature. Reid wrote the original draft and all co-authors contributed to writing and revision. Reid developed figure sketches and worked with visual artist Nicole Marie Burton to have them produced. Reid was interviewed on this subject on CBC Radio One's *Quirks & Quarks* in early 2020 (refer to **Appendix D**).

[4] **Reid AJ**, Cook KV, Wale TL, Middleton CT, Bass AL, Araujo HA, Alexander RA, Hinch SG, Cooke SJ. Combining Indigenous and Western fisheries sciences links ultimate fate of sockeye salmon bycatch with conditions of commercial capture and release. *In prep* for Ecological Applications.

The idea for this study was conceived by Reid, Cook, Hinch and Cooke, and field work was conducted collaboratively by the first five co-authors. Field work took place across the territories of multiple First Nations, and this research would not have been possible without permissions and substantial on-the-ground contributions from the Nisga'a Fisheries and Wildlife Department, with whom Alexander has been working as a senior biologist *via* LGL Limited since 1992. DNA analysis was conducted by Araujo at the DFO Pacific Biological Station. Reid maintained research relationships, conducted data analysis and wrote the original draft of this manuscript, and all co-authors have contributed (or will) to writing and revision before journal submission.

[5] **Reid AJ**, Moulton DA, Elmer LK, Kanigan AM, Patterson DA, Robinson KA, Araujo HA, Cooke SJ, Hinch SG. Survival of sockeye salmon following gillnet escape – in search of sustainable fisheries solutions. *In prep* for Conservation Science and Practice.

This project was conceived by Hinch and Cooke, as part of a multi-year program supported by a Natural Sciences and Engineering Research Council of Canada (NSERC) Strategic Grant. Field work was led by the first six co-authors, with additional support from the Pacific Salmon Ecology and Conservation Laboratory at the University of British Columbia and the Peters First Nation. DNA analysis was conducted by Araujo at the DFO Pacific Biological Station. Reid maintained research relationships, conducted data analysis and wrote the original manuscript draft, and all co-authors have contributed (or will) to writing and revision before journal submission.

[6] **Reid AJ**, Young N, Hinch SG, Cooke SJ. Indigenous knowledge of leading threats to wild Pacific salmon and aquatic health. *In prep* for People and Nature.

All co-authors conceived the idea for this research, contributed to methodological design and assisted with research ethics processes. Reid maintained research relationships, led interviews with knowledge holders and supervised work study student employees who assisted with interview transcription. Reid synthesized outcomes and wrote the original draft of the manuscript. All co-authors have contributed (or will) to writing and revision before journal submission.

Note: Other important collaborators were essential to realizing each of the above-listed research projects. Key people, groups, communities and governing bodies are identified and thanked in the Acknowledgements if they were not part of manuscript prep.

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Chapter 1: General Introduction

1.1 Fish Migrations, Multiple Stressors and Freshwater Conservation

The migration of fishes, or the cyclic and synchronous movement of fish species between "two worlds" to complete their life cycle (Dingle & Drake 2007), serves a wide range of functions both in ecosystems and societies. Fish migrations result in the flow of energy, materials and organisms from one place to another, which drives food web and ecosystem dynamics (Flecker et al. 2010). For instance, semelparous Pacific salmon (*Oncorhynchus* spp.) accumulate the vast majority of their body mass as they mature at sea, which then gets transferred into nutrient-limited freshwater ecosystems (*e.g.*, rivers, lakes and streams) when they return there to spawn and die (Groot & Margolis 1991). On spawning grounds, their eggs and bodies can be consumed directly by other organisms (*e.g.*, bears, wolves and eagles) and they influence food web processes through the bottom-up effects of increased productivity (Quinn 2018). Likewise, many human populations rely on predictable fish movements for subsistence harvest and livelihoods (*e.g.*, Hodgson et al. 2020), imprinting heavily on cultures, bodies of practice and management as well as systems of knowledge, belief and ceremony (**Figure 1-1**; Swezey & Heizer 1977; Stewart 2008). One renowned example is that of the First Salmon Ceremony (**Figure 1-1A**) which is practiced (with variation) by Indigenous peoples across the Northwest Coast of North America to mark and honour the annual return of migrating adult Pacific salmon (typically, Chinook salmon *O. tshawytscha*; Gunther 1926). This is an ancient tradition, passed down across generations, that carries with it to this day essential teachings of respect, reciprocity and responsibility, all tied to the stewardship of these migratory animals.

"Life on the move" is however an inherently challenging process (Dingle 2014) and migratory fishes are exposed to myriad physical (*e.g.*, extreme temperatures and flows, barriers) and biological (*e.g.*, predators, pathogens) stressors that can reduce their likelihood of survival as they travel between locations. Moving predictably in time and space (Lucas & Baras 2008) also makes these fish highly vulnerable to fisheries activities which introduce their own suite of additional concerns (*e.g.*, gear avoidance and escape, capture and release of non-target organisms or 'bycatch'), especially for diadromous fishes (*i.e.,* those that migrate between marine and fresh waters, like salmon) who are captured *en masse* where oceans narrow into river mouths and estuaries (McDowall 1999). Exposure to acute stressors (*e.g.*, a predator) yields reasonably predictable responses in fish (*i.e.,* elevated levels of circulating glucocorticoids which leads to physiological and behavioural changes; see Wendelaar Bonga 1997), allowing fish to overcome stressors in the short-term, while chronic stressors (*e.g.*, thermal stress) can produce more detrimental responses in fish (Barton 2002). For migratory fishes, their exposure to acute and/or chronic stressors, either simultaneously or sequentially, can impact their survival in ways that are difficult to predict. Stressor co-occurrence (*e.g.*, the release of bycatch at high temperatures) creates 'cumulative effects' that are not necessarily the sum of their parts, as stressors may interact in synergistic or antagonistic manners that heighten or lessen their impacts, respectively (Folt et al. 1999). Salmon (mainly sockeye salmon *O. nerka*) provide a pertinent example here as well, with previous studies linking migration failure with multiple stressors (*e.g.*, high flows and water temperatures; Rand et al. 2006), although most such studies have focused on just 1–2 stressors using primarily non-multivariate methods (see Johnson et al. 2012) – that is until more recently (*e.g.,* Teffer et al. 2017; Bass et al. 2018a, 2018b).

A recent global assessment, *The Living Planet Index (LPI) for Migratory Freshwater Fish,* identifies migratory fishes that use fresh waters – either exclusively or for part of their life cycle (like salmon) – to be in a particularly perilous position, with their populations declining globally by an average of 76% between 1970 and 2016 due to a range of aquatic threats (Deinet et al. 2020). This builds on earlier work that revealed that one of every three freshwater species are threatened with extinction (Collen et al. 2014) and that migratory freshwater fish are disproportionately threatened compared with other groups of fishes (Darwall & Freyhof 2016). A sobering example is that of the sturgeons and paddlefishes (Acipenseriformes) – *"living fossils"* (evolving hundreds of millions of years ago; Gardiner 1984) that are now on the brink of extinction in many cases, with 17 out of 27 species listed as Critically Endangered on the IUCN Red List (IUCN 2020) due to multiple stressors such as overfishing, pollution, habitat loss and barriers along their migration corridors (Katopodis et al. 2019). In contrast with Europe, the latest LPI report shows a less severe decline among North American migratory freshwater fishes (-26% *versus* -93%), but this may be driven by the fact that species like sturgeon and salmon had already been severely reduced in North America *before* 1970 (Humphries & Winemiller 2009; Deinet et al. 2020). 'Shifting baselines' pose a serious problem for effectively monitoring and reversing declines in the field of fisheries – *"a discipline that has suffered from lack of historical reflection"* (Pauly 1995). Serious and understudied freshwater threats are endangering migratory fishes around the globe, but the situation is not entirely hopeless as this latest LPI report also finds that protected and/or managed populations experience less severe declines, showing that potential gains can be made through fisheries regulations, dam removals and/or legal protections (Deinet et al. 2020).

1.2 Pacific Salmon Significance, Status and Stressors

"Salmon, the mainstay of our Nation. Not just the Nisga'a, but from Alaska to California. We're salmon people, our diet has been salmon for ... thousands of years. The disappearance of the salmon to me, is like the disappearance of the buffalo on the Great Plains of North America." –Sim'oogit Hleek Dr. Joseph Arthur Gosnell, Sr., CC OBC

"Perhaps no other organisms so epitomize the negative ecological consequences of human activity than the Pacific salmon. As much as the migratory bison characterized the pre-settlement Great Plains, so did the salmon define the rivers of the west coast of North America from California to Alaska. The great salmon migrations that once extended from bank to bank ... now reduced to a mere remnant." –(Dingle 2014 pg. 274)

By the same token that migratory organisms underpin critical functions in ecosystems and human cultures alike, it follows that declines in their abundances have caused major ecological and social disruptions. The disappearance of the bison (*Bison bison*; also known as buffalo) destabilized the cultural foundations of Indigenous peoples across North America (Dunbar-Ortiz 2014) and reshaped grassland environments (Gaston & Fuller 2008). Pacific salmon appear to be on a similar trajectory with more than 500 populations now extinct, primarily in their southern range and belonging to Chinook and sockeye species (Gustafson et al. 2007). Both bison and salmon have declined severely with the emergence of new stressors concomitant with colonization (**Figure 1-2**) – with the extermination of bison in fact reflecting a policy to create economic dependence and compliance in land transfers among Native American peoples[2] (Phippen 2016).

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[2] Another parallel some draw between the salmon and buffalo: *"We know that the U.S. Government devised a plan to defeat the Plains Indians. They killed off their food supply. Killed off the buffalo ... That's the way I look at what's happening to our salmon populations across British Columbia ... Disappearing, and nobody seems to be doing anything to stop that decline"* –Dr. Joseph Arthur Gosnell

Pacific salmon were, and remain, a vital aspect of Indigenous peoples' cultures, identities and knowledge systems across the Northwest Coast of North America who in a great many cases identify as "salmon people" (as noted above and discussed in greater detail in **Chapter 6**). For millennia before the Colonial period in North America, salmon were highly abundant and sustainably harvested not by chance, but rather through intricate and deliberate systems of stewardship as well as management[3]. These systems invoked place-based knowledges (used in the plural form to reflect their heterogeneity across distinct Indigenous cultures; Dei et al. 2000), context-specific harvesting technologies (*e.g.*, varieties of traps, nets and hooks; White 2006, Moss 2013) and management practices that reflected cultural laws, values and worldviews (Haggan et al. 2006; Turner & Berkes 2006; further discussed in **Chapter 4**). The emergence of industrial commercial salmon fisheries in the mid to late 19th century (**Figure 1-2B**), along with a variety of other significant ecological stressors (*e.g.*, widespread creation of dams; Avakyan & Iakovleva 1998; deterioration of critical habitats; Walters et al. 2008) as well as the disempowerment of Indigenous fisheries systems (*e.g.*, through the Canadian *Fisheries Act* of 1868), created a new ecological context for salmon where they would now have to traverse a gauntlet of threats to complete their anadromous life cycles (*i.e.,* migrating up transformed rivers from the sea to spawn). Wild salmon populations (or 'stocks') across the Pacific Northwest[4] are now thought to be less than 10% of their pre-1850s numbers (Lackey 2010), with a growing list of *Oncorhynchus* species and populations that are of serious conservation concern.

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[3] In the field of ecology, these two terms are often used interchangeably but their implications are quite distinct. Stewardship is an *ethic* that embodies notions of responsibility and respect for the natural world that has been entrusted in one's care through intergenerational transfer (Leopold 1989 [1949]; Reo et al. 2017), while the term management is more simply "the act of maintaining" – the set of practices and processes that are used in caring for the natural world (Chapin et al. 2010).
[4]Northern California, Oregon, Idaho, Washington, and the Columbia Basin portion of British Columbia.

In British Columbia (BC), Canada in 2005, the federal department of Fisheries and Oceans Canada (DFO) adopted *Canada's Policy for Conservation of Wild Pacific Salmon* (Wild Salmon Policy, WSP; Fisheries and Oceans 2005) recognizing a serious need for information on the status of the five species of anadromous salmon (sockeye, Chinook, chum *O. keta*, coho *O. kisutch* and pink *O. gorbuscha*) as well as pressures on their critical spawning and rearing habitats. A main strategy to aid in WSP salmon conservation and monitoring was the identification of species-specific Conservation Units[5] (CUs) that are genetically, ecologically and spatially distinct populations of wild salmon. Many of these CUs have diminished or are in decline (Price et al. 2017) and the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) has listed five CUs as Special Concern, three as Threatened, and ten as Endangered (Government of Canada 2018). Declines have been precipitous in BC's largest salmon producing system, the Fraser River (**Figure 1-3**), where a collapse of the return of sockeye in 2009 resulted in a closure of the fishery (for the third consecutive year) and precipitated a federal inquiry into their absence despite favourable pre-season estimated returns (*i.e.,* the *Cohen Commission of Inquiry into the Decline of Sockeye Salmon in the Fraser River*; Cohen 2012). The 2012 conclusion of this investigation identified *"no smoking gun"* but rather a suite of stressors responsible for the demise of sockeye, namely: infectious diseases and parasites; contaminants; aquaculture (emphasizing salmon farms); various fisheries activities and management; climate change; habitat loss (*e.g.*, through hydroelectric and industrial development projects); as well as cumulative stressor effects that arise through multiple stressor interactions.

There was widespread recognition at the time of the Cohen Commission, and it has

[5] DFO defines a CU as: *"A group of wild salmon sufficiently isolated from other groups that, if lost, is very unlikely to recolonize naturally within an acceptable timeframe (e.g., a human lifetime or a specified number of salmon generations)."* (Fisheries and Oceans Canada 2005).

only grown since, that key salmon stressors do behave in interactive manners. For instance, high water temperatures, which have been pronounced in the Fraser River (*i.e.,* ~2°C increase in peak summer river temperature over the past half century; Martins et al. 2011), stress salmon and increase their susceptibility to other stressors. Warm conditions leave Fraser sockeye, for example, with little aerobic scope for swimming (Eliason et al. 2011), meaning that they are less able to evade and/or overcome predators, high flows as well as fishing gears (English et al. 2011). When salmon interact with fishing gears but are not landed as catch (*i.e.,* they escape or are released as bycatch), they often experience some degree of physical injury and physiological stress which have been linked with both immediate and delayed mortality outcomes (Raby et al. 2015a), and this trend appears to worsen under warmer river conditions (Teffer et al. 2019). Significant questions remain about how the specific conditions of capture and release or escape from fisheries influence salmon survival in the context of other influential stressors, such as rising temperatures, given the evidence of strong local adaptations of salmon CUs to conditions in their natal rivers and streams (*e.g.*, pronounced differences in stock-specific thermal tolerances among Fraser sockeye populations, pointing to greater climate change resilience among certain CUs and heightened vulnerability among others; Eliason et al. 2011). Understanding and identifying ways to maintain CU diversity is crucial to the existence of resilient salmon populations, fisheries, economies and cultures moving forward. A central focus of this thesis is therefore to understand the consequences of the conditions of incidental capture and release (**Chapter 4**) and fisheries escape (**Chapter 5**) for Pacific salmon, especially for salmon CUs of conservation concern.

1.3 Salmon–Fisheries Interactions, Survival and Ultimate Fate

Salmon–fisheries interactions date back as long as humans have put trap, net or hook to water, but the scale of the problem has grown tremendously with the advent of industrial salmon fisheries and the emergence of co-occurring stressors such as climate change and introduced diseases. More fish come into contact with fishing gear than are retained as catch (Alverson et al. 1994), and simply put, these fish will either survive the interaction or they will not. What has been termed "fisheries-related incidental mortality" (FRIM) includes mortality of fish that encounter fishing gear but are not captured (*i.e.,* avoidance or escape) as well as that of fish that are captured but then discarded as bycatch (*i.e.,* on-board/immediate or post-release/delayed; Patterson et al. 2017). What has been made clear from a growing number of FRIM studies on salmon (largely from the two research teams that I belong to: Donaldson et al. 2011; Nguyen et al. 2014; Raby et al. 2015a, 2015b; Teffer et al. 2017, 2019; Bass et al. 2018a, 2018b; Cook et al. 2018a) is that the conditions of capture carry tremendous significance in shaping interaction outcomes. Fate (*i.e.,* survival or immediate/delayed mortality) varies with the magnitude of the fish's response (*e.g.*, injury, physiological stress) to different factors that can include intrinsic variables (such as sex, size, CU), extrinsic influences (such as water temperature or flow) as well as characteristics of the fishing interaction itself (such as the duration of the experience or the fishing gear/method used; reviewed by Patterson et al. 2017 and further discussed in **Chapters 4-5**). The need to account for FRIM in Pacific salmon stock assessments has long been recognized (Ricker 1976; then called "noncatch mortality"), and while DFO now uses FRIM to manage some salmon fisheries, the majority of estimated FRIM rates that are used stem from 24-hr holding studies conducted prior to 2001.

FRIM rates have been shown to be higher when studies are longer term (*i.e.,* more than 24 hours; Raby et al. 2015b) and conducted in realistic settings (such as *in situ* studies; Cooke et al. 2005) given that delayed mortality events and multiple stressor effects require time and true-to-life conditions to develop (Patterson et al. 2017; Lange et al. 2018). While short-term and lab-based studies can provide us with a clear mechanistic understanding of FRIM-related factors, where each variable can be carefully controlled and manipulated and biological responses readily monitored (*e.g.*, Teffer et al. 2017), there is also a need for long-term *in situ* studies that enable investigation into the 'ultimate fate' of salmon. Being semelparous, with a single lifetime reproductive event, the inability of salmon to reach their spawning grounds due to an earlier encounter with a fishery, and under potentially already stressful conditions, means a complete loss of fitness for the animal (Groot & Margolis 1991). Survival to spawning grounds is clearly crucial given the evident potential for population-level impacts, yet very few studies to date have monitored from the point of fisheries interaction (*i.e.,* release or escape location) through to life cycle completion (whereas monitoring to within a few hundred river kilometers from spawning grounds, due to logistic ease, is a more common approach; Bass et al. 2018b). Taken together, there is an apparent need for ultimate fate research that couples experimental fisheries approaches in the wild with multivariate analytical approaches (such as generalized linear models or survival analyses) to elucidate the conclusive consequences of fisheries interactions amidst multiple stressors for wild Pacific salmon. Furthermore, under rapidly changing ecological conditions, there is also a pressing need for current investigations and associated research outcomes to inform Pacific salmon management both in BC as well as across the Pacific Northwest.

1.4 Emerging Threats, Place-based Priorities and Indigenous Knowledge Systems

The list of multiple stressors that salmon (and fish in general) contend with is, however, neither static in time nor uniform across space. New aquatic threats are constantly emerging alongside rapidly expanding human populations, technological advancements and shifting climatic conditions (Arthington et al. 2016). Without current knowledge of threats recently emerged or those on the horizon, effectively managing fish populations and fisheries activities to cope with multiple stressors and their interactions becomes a considerable challenge. Being topographically low in the landscape and hydrologically connected systems, fresh waters incur particular risk as they are the *de facto* recipients of physical, chemical and biological inputs from the surrounding landscapes in which they are embedded. This may offer some insight into the particularly perilous position of migratory freshwater fishes, but until these threats are better characterized, anticipating how they will interact and shape fish survival outcomes (even on an individual stressor basis) remains difficult, if not impossible. Additionally, the varying levels of conservation concern across salmon CUs may in part be explained by asymmetries in the stressors they face and/or their impacts. As noted above, salmon populations have been shown to be highly unique and locally adapted to natal conditions, potentially influencing their ability to tolerate different stressors. Moreover, stressors themselves may pose a greater risk in one locale over another (*e.g.*, differential proximities to a contaminant source) so dissimilar influences on survival are to be expected. In addition to the need for new knowledge of emerging threats, especially for fresh waters, an improved understanding of how key concerns for salmon vary across contexts is also essential. Characterizing new threats (**Chapter 2**) and place-based priorities (**Chapter 6**) is thus a second focal area of this thesis.

Threat assessments can be achieved through a number of potential pathways (with an entire sub-discipline of social science being dedicated to the area of 'risk perception' as it relates to environmental perturbations; Keller et al. 2012), and here relying on expert judgement is deemed to be the most suitable approach for capturing the complexities of threats not yet fully developed (*i.e.,* emerging, and thus lacking strong documentation of quantified impacts in the scientific literature) as well as for understanding the nuances of key priorities and how they vary and interact across space and time as perceived and known by those who carry long-held, place-based knowledges of the system of interest. Revisiting the concern above around shifting baselines, this thesis creates purposeful space for historical reflection in fisheries by valuing the knowledge systems and experiences held by Indigenous peoples who live in relationship with salmon and the fishery, and who carry stories, experiences and knowledges from generations upon generations past to effectively steward them. Indigenous knowledge systems are not antiquated, simplistic or necessarily unquantifiable viewpoints – they comprise contemporary and complex understandings and systems of practice that are both traditional[6] (*i.e.,* passed down across generations) and scientific[7] (*i.e.,* systematic expertise of the natural world arrived at through observation and experiment). A third and final focus of this thesis is to explore the application of the Mi'kmaw conceptual framework of "Two-Eyed Seeing"[8] (**Chapter 3**) that promotes co-existence between Western scientific and Indigenous ways of knowing to create new, inclusive and better-informed approaches for fisheries research and management in future.

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[6] *"Longstanding knowledge, practice, and belief, developed from experience gained over centuries and adapted to the local culture and environment, handed down through the generations"* –(Berkes 2018 pg. 8)

[7] *"Systematic enterprise that gathers and condenses knowledge into testable laws and principles"* –(Wilson 1999 pg. 58)

[8] *"Learning to see from one eye with the strengths of Indigenous knowledges and ways of knowing, and from the other eye with the strengths of mainstream knowledges and ways of knowing, and to use both these eyes together, for the benefit of all"* –(Bartlett et al. 2012)

1.5 Thesis Themes and Objectives

My overarching objective through this body of work is to help build collective understanding of leading aquatic stressors and their implications for Pacific salmon who have essential roles to play in our ecosystems and societies alike, as both ecological and cultural keystone species (Willson & Halupka 1995; Garibaldi & Turner 2004). This thesis adopts approaches that are both hypothesis-testing as well as exploratory (*i.e.,* hypothesis-generating) exercises, and it draws from a range of disciplines spanning the natural, social and Indigenous sciences[9]. Many of my thesis chapters are strategically positioned to privilege the voices and expertise of Indigenous peoples given long histories of suppression both in the academe and in the realm of contemporary fisheries management. This work is enriched by strong and diverse partnerships with individuals, groups, communities and governing bodies across a variety of contexts, including leading freshwater scientists from around the world (**Chapter 2**), thought leaders in the nascent academic discipline of Indigenous science (**Chapter 3**), Pacific salmon fishers and managers who span much of the range of BC salmon (**Chapters 4-5**), and Indigenous knowledge holders spread across BC's largest salmon producing systems (**Chapter 6**): the Fraser, Skeena and Nass Rivers (**Figure 1-3**). These partnerships allow me to couple expert threat assessments with experimental fisheries approaches and to draw on Two-Eyed Seeing as a conceptual foundation to create the "ethical space"[10] needed for knowledge co-existence (**Figure 1-4**). From here, I can approach several key research areas that would otherwise be inaccessible.

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[9] *"Scientific knowledge* [as defined on the previous page] *of peoples who, as participants in culture, are affected by the worldview and interests of their home community."* –(Snively & Corsiglia 2016).

[10] *"The "ethical space" is formed when two societies, with disparate worldviews, are poised to engage each other. It is the thought about diverse societies and the space in between them that contributes to the development of a framework for dialogue between human communities."* –(Ermine 2007)

Chapter 2 provides a synthesis of emerging freshwater threats to aid in explaining why freshwater population declines continue to outpace contemporaneous losses in marine and terrestrial ecosystems. Key concerns identified herein (*e.g.*, climate change, infectious diseases, cumulative stressors) shape activities undertaken in field studies across BC. **Chapter 3** is a review of Two-Eyed Seeing and an exploration of its application to fisheries. It centers around the assertion that Western science, despite its perceived objectivity and superiority, is not enough for solving many of our ongoing fisheries crises. This framework provides a foundation for the field investigations undertaken in the rest of the thesis. **Chapter 4** combines Indigenous and Western fisheries sciences to study the ultimate fate of sockeye that are incidentally captured by marine commercial purse seine fisheries and released as bycatch on BC's North Coast. By combining biotelemetry with a variety of other tools in my Nation's territory, the Nisga'a Nation, I was able to run robust survival analyses linking sockeye fate with initial conditions of capture, pointing to actionable strategies for management and yielding new knowledge about context-specific survival. **Chapter 5** also adopts an experimental fisheries approach, examining instead sockeye survival following gillnet escape in the Fraser River. Ultimate fate is again assessed using biotelemetry, and here too survival analyses connect migration failure with the magnitude of fish responses to intrinsic, extrinsic as well as fishing factors. This work points to specific modifications to fishing practices and gears that could promote salmon survival. **Chapter 6** centers on improving our understanding of place-based priorities for salmon by learning from Indigenous knowledge holders across BC through collaborative research partnerships. Across study regions, some key concerns are shared (*e.g.*, salmon farms, climate change) while others were localized, reflective of place-based knowledge systems.

Finally, in the general conclusion (**Chapter 7**), I draw together (in brief) the major theoretical, applied and methodological advancements made by this research. Throughout this thesis, I place emphasis on the research choices made and actions taken to uphold the responsibilities that come with work conducted at the interface of Western science and Indigenous knowledge systems. Given a very fraught history between educational and research institutions and Indigenous communities in the land now known as Canada, there is tremendous work to be done to ensure that these ways of knowing and all that they are tied to – the environment from which they emanate and the keepers who carry them – are protected now and in future.

1.6 Figures

Figure 1-1 Image set showing the historical and contemporary imprinting of migratory fishes on Indigenous cultures across North America. (A) The end of the Kwantlen First Nation's First Salmon Ceremony (located on McMillan Island near Fort Langley, British Columbia), where Elders and community members in regalia return the bones from the first Pacific salmon harvest of the year to the water. (B) "Serpent People" – a theatrical performance based on Anishinaabe stories of 'The Black Sturgeon' from Nipissing First Nation, told by Aanmitaagzi's Perry Mcleod-Shabogeesic. (C) My ancestor Noah Dangeli, who sits with his catch of Pacific halibut in Gingolx, British Columbia circa 1910 (photographer unknown; image from "Memories of Kincolith" Facebook group). (D) A Pacific halibut totem stands in Totem Bight State Historical Park near Ketchikan, Alaska (gateway to Gingolx and the Nass River Valley before the road was built). Image source is public domain unless noted otherwise.

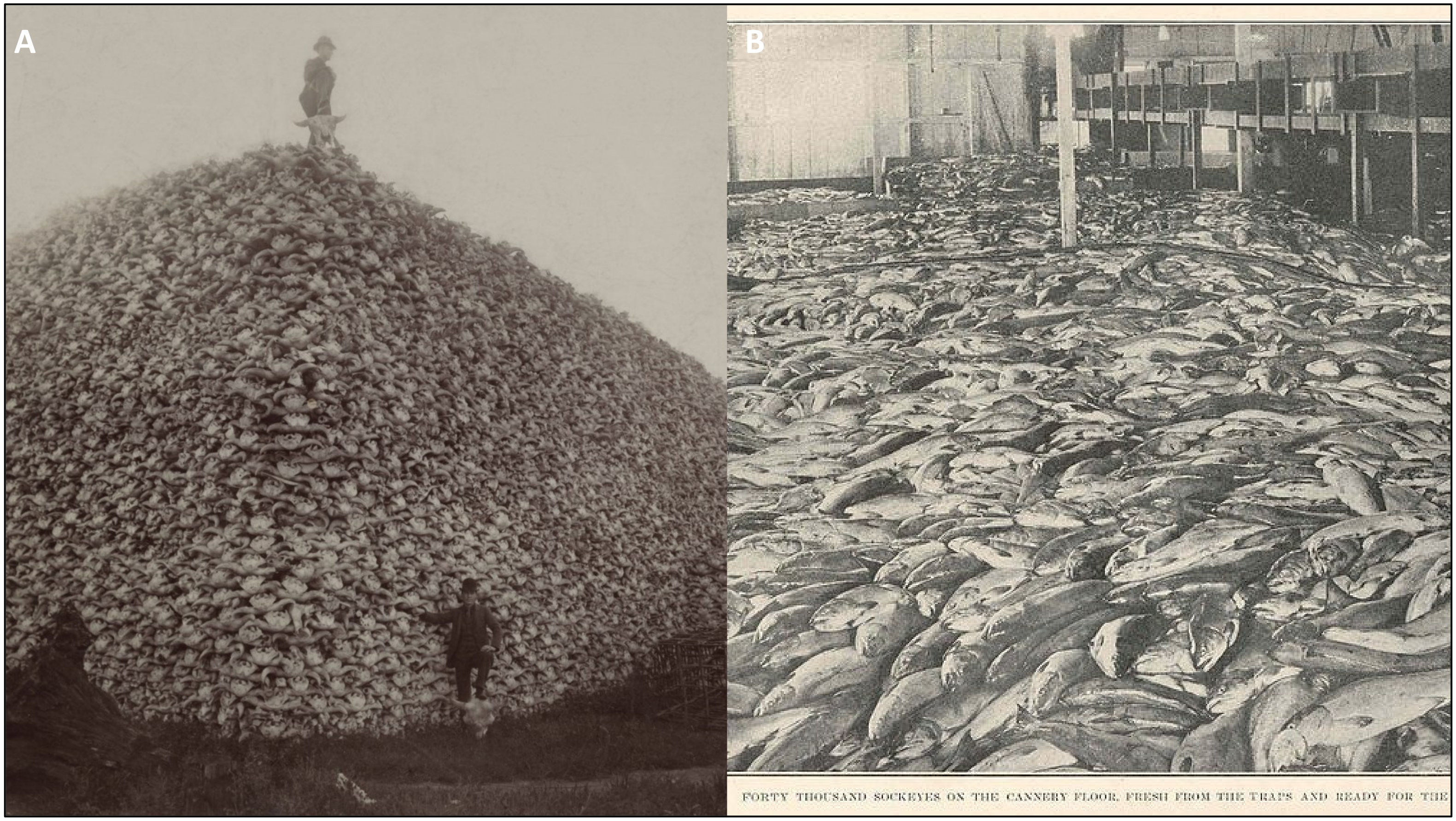

Figure 1-2 Overharvested migratory animals in the late 19th century.
(A) A pile of bison skulls awaiting industrial processing in Detroit, Michigan circa 1892 (source: Burton Historical Collection, Detroit Public Library). (B) "Forty thousand sockeyes on the cannery floor, fresh from the traps and ready for the Iron Chink[11]" in Seattle, Washington circa 1906 (source: public domain).

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[11] In the early 1900s, machines named "Iron Chinks" began replacing the largely Chinese cannery workers, responsible for butchering and canning salmon. The use of a racial slur in the machine's name is reflective of the severe discrimination faced by Chinese immigrants in North America. The name was used until the mid-20th century – now they are called iron butchers or butchering machines (University of Washington Libraries 2020).

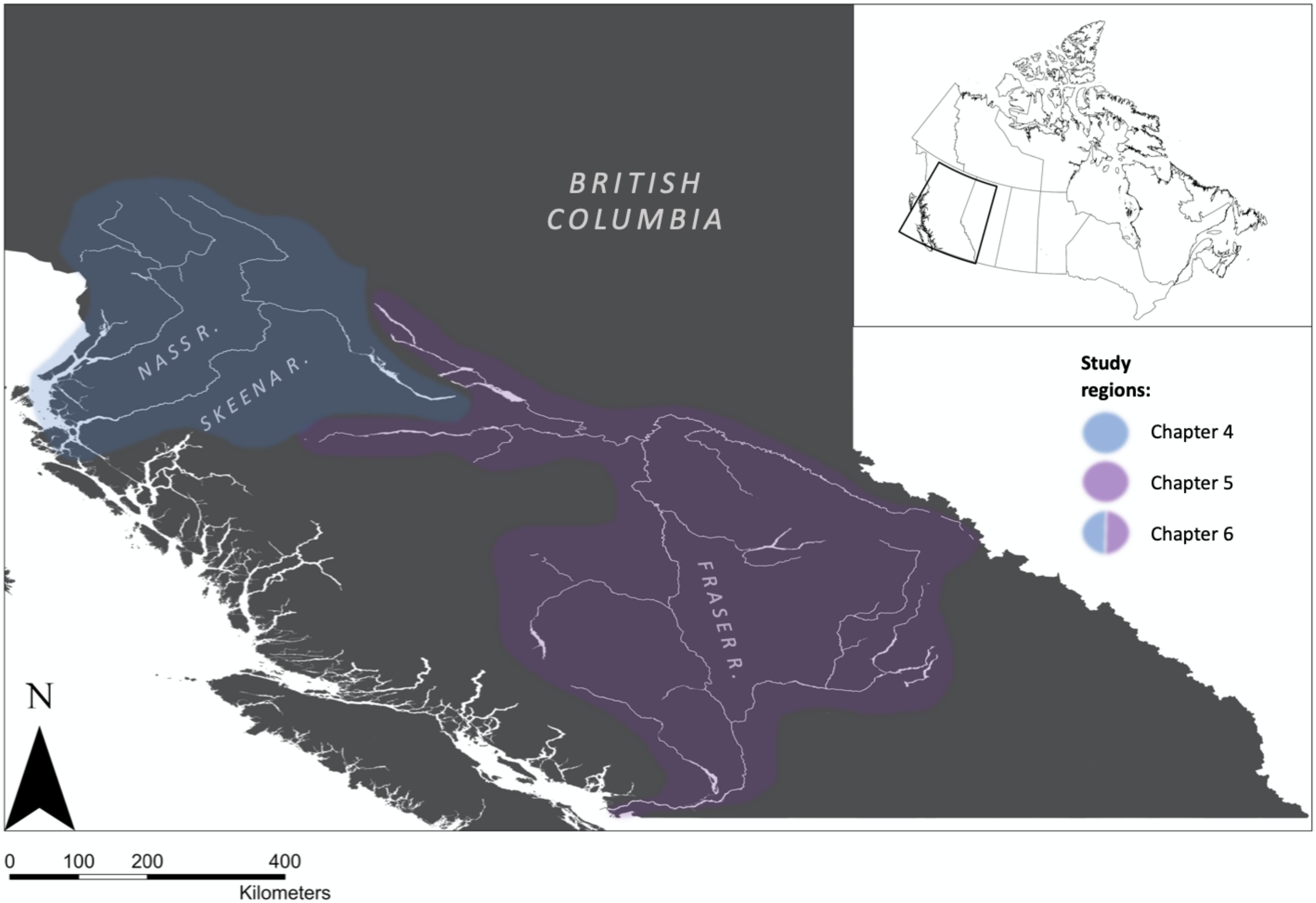


Figure 1-3 Map of British Columbia's three largest Pacific salmon producing river systems (Fraser, Skeena and Nass Rivers) where doctoral studies were focused between 2016 and 2018.
Geospatial data used to create this map are from the British Columbia Freshwater Atlas (Ministry of Forests, Lands, and Natural Resource Operations 2011).

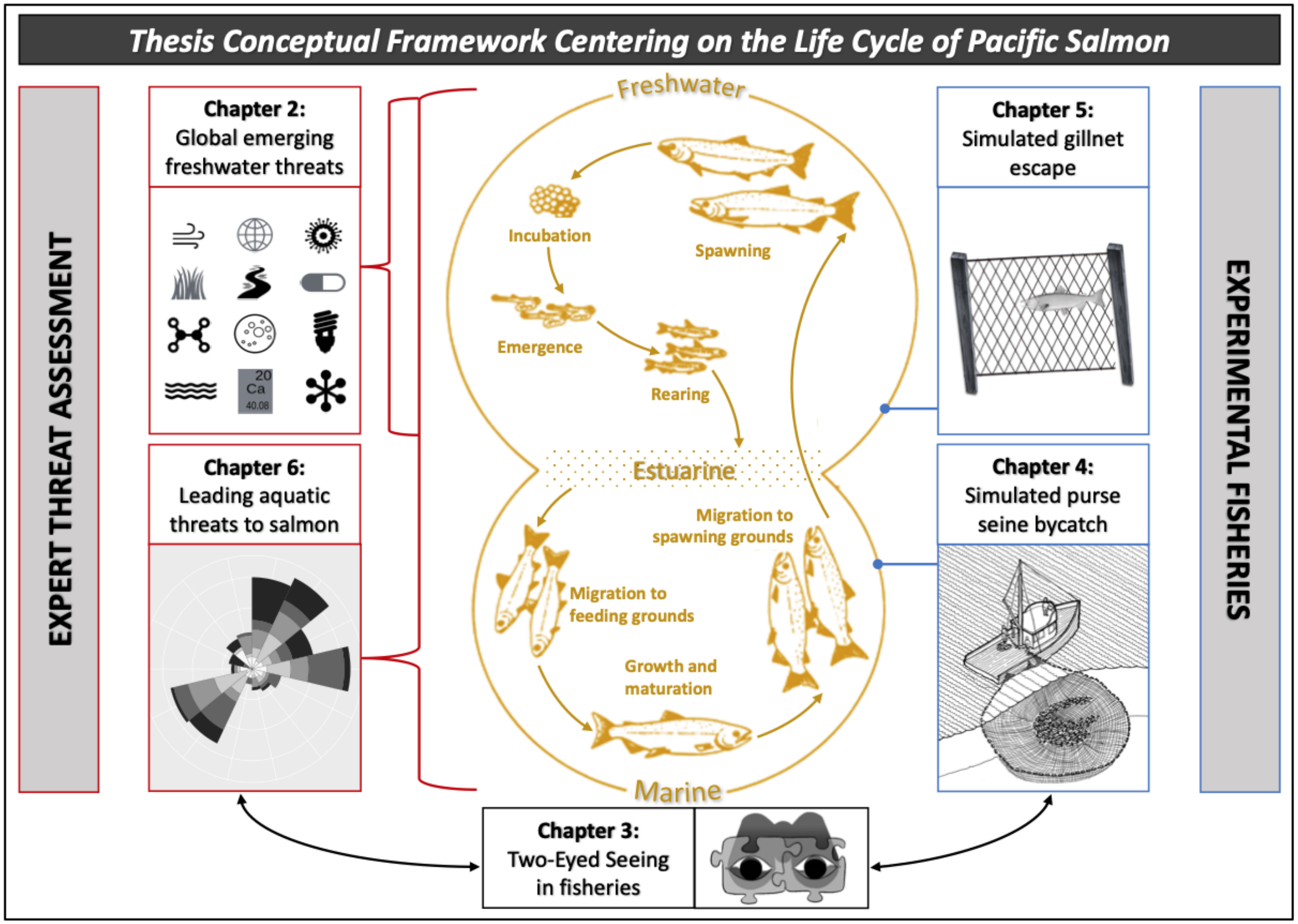


Figure 1-4 Conceptual framework centering on the life cycle of Pacific salmon, illustrating the focus and linkages between thesis chapters. Chapters 2 and 6 (left; red borders) comprise expert threat assessment exercises involving international freshwater scientists and Indigenous knowledge holders from British Columbia's three largest salmon-producing systems, respectively. Chapters 4 and 5 (right; blue borders) involve experimental fisheries studies to investigate salmon survival in two distinct multiple stressor contexts, following salmon (i) release as bycatch and (ii) escape from fisheries, respectively. Chapter 3 explores the need and potential for the application of a Two-Eyed Seeing framework that promotes knowledge coexistence between Western science and Indigenous ways of knowing in fisheries research and management. This thinking informed (and was in turn informed by) activities undertaken in Chapters 4 and 6, shown by double-headed arrows. Images are drawn from their respective chapters (2,3,5,6) or modified from the public domain (4, life cycle).

Chapter 2: Emerging threats and persistent conservation challenges for freshwater biodiversity

2.1 Abstract

In the twelve years since (Dudgeon et al. 2006) reviewed major pressures on freshwater ecosystems, the biodiversity crisis in the world's lakes, reservoirs, rivers, streams and wetlands has deepened. While lakes, reservoirs and rivers cover only 2.3% of the Earth's surface, these ecosystems host at least 9.5% of the Earth's described animal species. Furthermore, using the World Wildlife Fund's Living Planet Index, freshwater declines (83% between 1970–2014) continue to outpace the contemporaneous declines in marine or terrestrial systems. The Anthropocene has brought multiple new and varied threats that disproportionately impact freshwater systems. We document twelve emerging threats to freshwater biodiversity that are either entirely new since 2006 or have since intensified: (1) *changing climates*; (2) *e-commerce and invasions*; (3) *infectious diseases*; (4) *harmful algal blooms*; (5) *expanding hydropower*; (6) *emerging contaminants*; (7) *engineered nanomaterials*; (8) *microplastic pollution*; (9) *light and noise*; (10) *freshwater salinisation*; (11) *declining calcium*; and (12) *cumulative stressors*. Effects are evidenced for amphibians, fishes, invertebrates, microbes, plants, turtles and waterbirds, with potential for ecosystem-level changes through bottom-up and top-down processes. In our highly uncertain future, the net effects of these threats raise serious concerns for freshwater ecosystems. However, we also highlight opportunities for conservation gains as a result of novel management tools (*e.g.*, environmental flows, environmental DNA) and specific conservation-oriented actions (*e.g.*, dam removal, habitat protection policies, managed

relocation of species) that have been met with varying levels of success. Moving forward, we advocate hybrid approaches that manage fresh waters as crucial ecosystems for human life support as well as essential hotspots of biodiversity and ecological function. Efforts to reverse global trends in freshwater degradation now depend on bridging an immense gap between the aspirations of conservation biologists and the accelerating rate of species endangerment.

2.2 Introduction

It has been over a decade since Dudgeon et al. (2006) published their seminal review of ecological stressors responsible for global freshwater biodiversity decline. This authoritative paper has been cited over 1800 times, placing it among the top-cited 1% of papers in the field of Biology and Biochemistry (Web of Science®). Dudgeon et al. (2006) identified 'overexploitation', 'water pollution', 'flow modification', 'destruction or degradation of habitat' and 'invasion by exotic species' as five leading causes of population declines and range reductions of freshwater organisms worldwide. However, over the last decade, and as we advance into the epoch now being referred to as 'The Anthropocene' (Crutzen 2006), these threats have escalated and/or evolved, and new or previously unrecognized threats have become more apparent. The current scale of biodiversity loss in fresh waters is now so rapid that we consider it an invisible tragedy – hidden beneath the water surface (Richter et al. 1997) – that attracts little public, political or scientific interest (Cooke et al. 2016). It is timely, therefore, to revisit the questions: which emerging threats pose the greatest challenge to freshwater biodiversity conservation, and where do opportunities for intervention exist?

This overview identifies these emerging threats and updates our knowledge of continuing challenges to freshwater conservation, paying special attention to issues that may have global, undesirable effects. The scope includes: (1) threats identified by expert opinion and supported by primary literature; (2) threats that vary in magnitude, geographic extent and/or frequency around the world; and (3) threats that are entirely novel since 2006 (see **Section 2.3.7** Engineered Nanomaterials), or previously known issues with trajectories that require renewed consideration (see **Section 2.3.9** Light and Noise). We begin by describing the status of global freshwater biodiversity and changes identified since Dudgeon et al. (2006). Twelve emerging threats are discussed and exemplified using diverse taxonomic groups with examples of mitigation provided where possible. We close with a discussion of the risks and benefits of various conservation tools, finally describing areas of conservation optimism that could contribute to a "good" Anthropocene (Bennett et al. 2016) for freshwater biodiversity.

2.2.1 Freshwater Biodiversity: A Deepening Crisis

Fresh waters comprise only 0.01% of the water on Earth, with lakes, reservoirs and rivers covering approximately 2.3% (and freshwater wetlands encompassing an estimated 5.4-6.8%) of the global land surface area, excluding large ice sheets (Lehner & Döll 2004). An initial global inventory, FABA – the Freshwater Animal Biodiversity Assessment (Balian et al. 2008) – revealed that these ecosystems host almost 9.5% of the Earth's described animal species, including one-third of vertebrates, and wetland ecosystems which are highly biodiverse were not included in FABA. Despite the much greater area and total production of marine environments, the species richness of marine and freshwater fishes (Actinopterygii) is similar (14,736 and 15,149 species, respectively), with all saltwater species derived from a freshwater ancestor (Carrete Vega & Wiens 2012).

Alarmingly, indicators are revealing rapid population declines and a large extinction risk in freshwater organisms. The World Wildlife Fund (WWF) Living Planet Index (LPI; Collen et al. 2009) disclosed that the index for populations of freshwater species is falling more steeply from 1970–2012 than either the index for marine or terrestrial populations (**Figure 2-1**). The LPI for freshwater vertebrates has declined by 81% (range 68–89%) relative to index declines of 38% and 36% for land and sea, respectively; by 2014, this value for freshwater ecosystems had risen to 83% (WWF 2018). This represents an annualized index decline of 3.9% for monitored freshwater populations, which is close to four times greater than that of terrestrial populations (1.1%). In this analysis, all 881 freshwater species (and 3,324 populations) used to calculate the LPI are vertebrates, with detectable taxonomic and biogeographic biases across the data sets available. How the reported LPI trends relate to that of broader biodiversity remains largely unknown (Collen et al. 2009). Nonetheless, other data, such as the International Union for Conservation of Nature (IUCN) Red List, confirm the high proportion of threatened species among freshwater-associated vertebrates (Ricciardi & Rasmussen 1999; Collen et al. 2014). For example, almost 40% of European and North American freshwater fishes are at risk (Kottelat & Freyhof 2007; Jelks et al. 2008). Although less comprehensively recorded than vertebrates, freshwater invertebrates are also faring worse than their terrestrial counterparts (Taylor et al. 2007; Clausnitzer et al. 2009; Cumberlidge et al. 2009).

Despite the downward trajectory of many freshwater taxa, the conservation literature is persistently biased towards terrestrial organisms, with fewer than 20% of recent papers dealing with aquatic species (Di Marco et al. 2017). This is problematic for at least three reasons. First, terrestrial biodiversity indicators are a poor surrogate for fresh waters (Darwall et al. 2011). Second, while some primary solutions to freshwater conservation problems depend on management at the terrestrial-freshwater interface (*e.g.*, reduced agricultural runoff), many land-based conservation efforts for freshwater biodiversity require implementation over large spatial extents at channel, riparian or catchment scales (Darwall et al. 2011). For example, 84% of threatened freshwater megafauna ranges fall outside of existing protected areas (Carrizo et al. 2017). Finally, freshwater ecosystems represent hotspots of endangerment as a result of the convergence between biological richness and the many forms of human freshwater exploitation that are not only generated by land-based actions. Projecting these issues forward suggests that freshwater extinction risks will remain high over the next few decades, regardless of actions taken now, due to an incurred 'debt' arising from low-viability populations that are in the process of dwindling to extinction (Strayer & Dudgeon 2010). Nor will anthropogenic pressures on freshwater ecosystems soon ease, in view of the threats reviewed herein, particularly the ambitious plans for water infrastructure development globally (see **Section 2.3.5** Expanding Hydropower) as well as through expanding population pressure and the growing needs for domestic water use and food production (Mekonnen & Hoekstra 2016).

2.2.2 Persistent Threats to Freshwater Biodiversity

Habitat degradation is a leading and persistent cause of population declines in freshwater systems (Dudgeon et al. 2006; WWF 2018). While this threat is ubiquitous as a risk to biodiversity in nearly all biomes and freshwater ecosystem types on Earth, it is likely to be augmented or exacerbated as new threats emerge (see **Section 2.3.12** Cumulative Stressors). For example, while water pollution is well-established in the degradation of freshwater ecosystems (Cope 1966), the pollutants and processes involved are rapidly changing (see **Section 2.3.6** Emerging Contaminants). The Earth's surface under land management with high pollution risk (*e.g.*, urban zones, cropland) is increasing as the global human population expands (Martinuzzi et al. 2014).

Habitat degradation through flow modification is another persistent threat to global freshwater biodiversity (see **Section 2.3.5** Expanding Hydropower) (Dudgeon et al. 2006). Thousands of dams are planned or under construction worldwide (Zarfl et al. 2015), with little or no consideration of their ecological consequences (Winemiller et al. 2016). Freshwater ecosystems are at risk of incurring one or more of the well-studied effects of dam-induced flow modification (*e.g.*, reduced discharge, impaired fish migration, decreased river-floodplain connectivity) (Juracek 2015). In addition, by decreasing fish abundance and biodiversity, dams pose threats to fish-based economies and the food security of individuals who rely on fishes (Orr et al. 2012). They can also create or exacerbate infectious disease threats by enhancing transmission opportunities for water-related parasites (*e.g.*, Steinmann et al. 2006). Moreover, climate change is expected to alter hydroclimates and increase sea levels (see **Section 2.3.1** Changing Climates), with potentially harmful socioeconomic and ecological effects on humans and ecosystems in coastal areas (see **Section 2.3.10** Freshwater Salinisation).

Overexploitation of organisms for consumption (primarily fishes, certain aquatic invertebrates) is another major driver of freshwater biodiversity loss (Dudgeon et al. 2006; WWF 2018; He et al. 2017), which has long been recognized (Allan et al. 2005; Pikitch et al. 2005) and in some areas curtailed (Buszkiewicz et al. 2016). Overexploitation includes both targeted harvest and mortalities through bycatch. Although once thought to be primarily a problem of marine fisheries (Alverson et al. 1994), bycatch also affects a wide range of freshwater taxa (Raby et al. 2011). While the magnitude and extent of exploitation are greater in marine systems than fresh waters (Arthington et al. 2016), there are several key examples where overexploitation of freshwater fishes continues as a persistent freshwater threat (with an entire sub-discipline of social science being dedicated to the area of 'risk perception' as it relates to environmental perturbations; Dudgeon et al. 2006; Keller et al. 2012).

Other significant drivers of freshwater biodiversity decline are invasive species and disease (Dudgeon et al. 2006; WWF 2018). In a global meta-analysis of 151 publications and 733 separate cases of invasive species incursions in aquatic ecosystems from 1994 to 2014, Gallardo *et al.* (2016) documented strong negative effects on the abundances of macrophytes, zooplankton and fish. In a globalized world where people, materials and information move constantly (see **Section 2.3.2** E-commerce and Invasions), invasive species are particularly threatening in freshwater ecosystems. They, like islands, are historically isolated but increasingly connected through human actions that facilitate invasive species dispersal and transport (Gherardi 2007). Increasing connectivity also facilitates the transmission of novel pathogens and disease (see **Section 2.3.3** Infectious Diseases), with implications for both human well-being and wildlife conservation.

2.2.3 Foreseeing the Foreseeable

Although challenging, predicting the effects of threats to fresh waters aids the identification of gaps in knowledge and policy (Sutherland et al. 2007), while fostering informed decision-making. By 'foreseeing the foreseeable', practitioners can prioritize research, plan strategically and manage risk to enable improved management and conservation of fresh waters. While there are "emerging threats" reviews for terrestrial (*e.g.*, Estrada et al. 2017) and marine (*e.g.*, Harvell et al. 1999) systems, they are often habitat- or issue-specific (*e.g.*, Calmon et al. 2011), and we know of no such recent publication for freshwater biodiversity. This synthesis of global freshwater stressors is therefore intended to help identify emerging threats and inform prediction, management decision-making, mitigation and conservation action.

2.3 Emerging Threats

Although not exhaustive, 12 pressing and emerging threats to freshwater biodiversity have been identified by expert opinion and supporting primary literature. These threats vary in their geographic extent, severity of effects and degree of understanding (see **Table 2-1**).

2.3.1 Changing Climates

Although examples of species extinction or impairment linked clearly to climate change are still scarce (Durance & Ormerod 2007, 2010), climate change potentially threatens ~50% of global freshwater fish species (Darwall & Freyhof 2015). Ecological responses to an average warming of only ~1°C are already apparent. Of 31 ecological processes that underpin freshwater ecosystem functioning from genes to populations, 23 have been affected by climate change, including reductions in body size, shifts in distribution, changes in phenology, algal blooms and desynchronization of interspecific interactions (Scheffers et al. 2016).

Persistent freshwater threats from climate change include increasing water temperatures, altered discharge and interactions between these and other stressors (see **Section 2.3.12** Cumulative Stressors) (Ficke et al. 2007; Heino et al. 2009; IPCC 2014). Rising freshwater temperatures can alter species distribution (Parmesan 2006), disease outbreaks (Hermoso 2017), phenology (Krabbenhoft et al. 2014) and survival (Bassar et al. 2016). Changing flow regimes are geographically variable, but variations in annual precipitation, storm events, floods and droughts are predicted to intensify in northern Europe, endangering molluscs and other species (Hastie et al. 2003), while in more arid regions such as Australia, rainfall and river flows are anticipated to decrease, threatening waterbirds and other species (Pittock et al. 2008).

Extreme events are anticipated to become more prevalent (IPCC 2014), with rates of change and unpredictability exceeding what can be accommodated by species' evolution (Brook et al. 2008; Loarie et al. 2009). As well as warming, rapid decreases in water temperature (termed 'cold shock') might also occur in some locations. For example, a 2010 cold shock event in Bolivia caused mass mortality of fishes in the Amazon (Szekeres et al. 2016). Already, over half of the world's rivers are characterized by periodic drying events, but increased frequency and intensity of droughts (Milly et al. 2002) will see many perennial rivers transition to intermittent rivers (Datry et al. 2016). Physical and chemical properties of fresh water are also changing, for example the timing of ice formation and break-up are shifting on a global scale (Magnuson et al. 2000). Changes in lake stratification are likely to magnify hypolimnetic hypoxia and affect lake productivity

(Kraemer et al. 2015), restricting pelagic habitat availability for many species (Ficke et al. 2007). Increasing water temperatures and CO_2 concentrations are expected to favor cyanobacteria over eukaryotic algae, making it imperative to limit nutrient inputs to mitigate harmful blooms (Visser et al. 2016) (see **Section 2.3.4** Harmful Algal Blooms).

Climate change is further anticipated to amplify many of the emerging concerns identified in this paper (*e.g.*, invasive species (Rahel & Olden 2008), pathogens (Marcogliese 2008), eutrophication (Elliott 2012), hydropower (Knouft & Ficklin 2017), salinity (Henman & Poulter 2008), although in some cases it could function to mitigate certain threats). In anticipation of shifting precipitation and temperature, humans are further altering flow regimes by constructing dams and "hard" engineering projects to protect against floods, increase water storage and enhance irrigation capacity (Palmer et al. 2008). Global government commitments to reduce greenhouse gas (GHG) emissions (that would build on the 2015 Paris agreement), expand freshwater protected areas (Pittock et al. 2008) and restore habitats to provide refugia for thermal adaptation (Heino et al. 2009) are critical to mitigate the effects of climate change on freshwater biodiversity.

2.3.2 E-commerce and Invasions

Invasive species are a primary threat to freshwater biodiversity, and modes of species introductions may develop further in the future (Rahel & Olden 2008). Global trade and the associated movement of live organisms are long-standing primary pathways for biological invasions (Levine & D'Antonio 2003; Perrings et al. 2005), but developing vectors (transportation mechanisms) and trade routes (geographic paths between source and recipient regions) pose an emerging conservation challenge. Specifically, the recent surge in global electronic commerce (e-commerce) linked to Internet sales of novel invasive species (*e.g.*, Walters et al. 2006; Humair et al. 2015) may be expanding potential links among established and emerging trade partners, concomitant with changes in societal attitudes towards unusual pets (Prokop & Randler 2018) and non-native species (Humair et al. 2014). Large and small "brick and mortar" stores traditionally played a significant role in the pet, aquarium and horticulture trade (Reichard & White 2001; Padilla & Williams 2004), often culminating in pet owners releasing unwanted organisms into natural waterbodies (Gertzen et al. 2008). Interestingly, some of the most popular fish sold are also the most likely to become established in the wild (Duggan et al. 2006). Individual hobbyists, collectors and breeders can now easily participate in an Internet species market (Tissot et al. 2010). These largely unregulated activities challenge current management, policy and educational strategies aiming to address live-trade pathways (Strecker et al. 2011).

Recent evaluations have highlighted the significant role of e-commence in the trade of nonnative plants and animals. Aquatic weeds are sold internationally through the Internet in several regions (Kay & Hoyle 2001; Walters et al. 2006; Martin & Coetzee 2011), and more invasive than non-invasive plant species are available on major online auction websites (Humair et al. 2015). Broad overviews identify e-commerce as a significant contributor to national-level biosecurity risk (*e.g.*, Parrott & Roy 2009; Derraik & Phillips 2010). In large Brazilian cities such as São Paulo and Rio de Janeiro, non-native fishes from the Amazon, Australia, Southeast Asia and Africa are sold without apparent restrictions (Magalhães 2015). Global environmental change may also intensify and shift the geographic routes of e-commerce trade. (Bradley et al. 2012) demonstrated how climate change and water restrictions may increase demand for horticultural species adapted to warm and dry environments. The net result is the creation of novel modes of long-distance dispersal (Lenda et al. 2014).

Managing e-commerce risks is challenging. The array of mechanisms for making transactions is diverse, including standard retail websites, auction sites, local businesses, wanted ads, online portals and chat fora (NISC 2012). Social media is further complicating the landscape, particularly through informal retail (Magalhães et al. 2017). Web crawlers have been used to monitor the Internet for the sale of illegal animals and plants (Sonricker Hansen et al. 2012); similarly, enforcement authorities could use Internet tools such as machine-learning algorithms to identify sellers of prohibited invasive species (Di Minin et al. 2018). Other tools focusing on accountability may seek to educate buyers, for example with online warning labels or pop-ups when an invasive species is about to be purchased. Increasing outreach and education to enhance buyer and seller awareness of invasive species remains paramount.

2.3.3 Infectious Diseases

Fresh waters are often transmission foci for human and wildlife pathogens (Johnson & Paull 2011; Okamura & Feist 2011). Because of the importance of water to the survival of most life forms, freshwater ecosystems often function as reliable yet concentrated hotspots of multi-species interactions. The aquatic medium also facilitates the survival of many parasitic infectious stages (by preventing desiccation) as well as their likelihood of contact with potential hosts, either directly or indirectly via ingestion. The biphasic life cycles of some freshwater taxa (*e.g.*, aquatic insects, amphibians) also link infections across ecotones. As a result, many microparasites (*e.g.*, viruses, fungi, protozoans, bacteria) and macroparasites (*e.g.*, flukes, roundworms, tapeworms, arthropods) depend on freshwater hosts for transmission (Marcogliese 2008; Johnson & Paull 2011). Many new infectious diseases are themselves invasive species, and some are transmitted by non-native taxa.

In some cases, infections can dramatically affect freshwater biodiversity. Introduced diseases (*e.g.*, crayfish plague and salmonid whirling disease), for instance, have devastated native taxa (*e.g.*, European crayfish and North American salmonids, respectively) (Hoffman 1990; Holdich & Reeve 1991). The global spread of chytridiomycosis caused by the fungal pathogen *Batrachochytrium dendrobatidis* (Bd) has been linked to the extirpation or extinction of 200 species of frogs and toads (Rödder et al. 2009). A second, recently-discovered invasive chytrid (*B. salamandrivorans*) is expected to be similarly problematic for salamander species in Europe and North America (Feldmeier et al. 2016). Collectively, these epizootics have significant community- and ecosystem-level effects. As examples, crayfish plague indirectly enhanced macrophyte and mollusc populations (Alderman et al. 1984), whirling disease caused diet shifts in bears and birds (Koel et al. 2005), and Bd altered algal growth and nutrient cycling in tropical streams (Whiles et al. 2013).

The relative importance of infectious diseases in threatening freshwater biodiversity, however, remains incompletely understood (Daszak et al. 2000). Johnson and Paull (2011) presented evidence of increased incidence of water-related disease in amphibians, freshwater fishes and crayfishes over the past 40 years (1970–2009). For amphibians, there was a >4-fold increase in disease-related research and reports on Bd, ranavirus and infection by flukes, with ranaviral infections also linked to turtle die-offs (Johnson et al. 2008). Fishes had the highest volume of research and broadest pathogen diversity; viral infection such as viral hemorrhagic septicemia and infectious salmon anemia have spread from marine environments and aquaculture, respectively (Murray et al. 2002). Emerging diseases, such as proliferative kidney disease (PKD), reflect warmer temperatures (Okamura et al. 2011), and in 2016, PKD caused a die-off of 10,000 fish in the Yellowstone River following an unusual warming event. For crayfishes, white spot syndrome and porcelain disease have caused population-level declines, often in association with aquaculture, alongside the ongoing effects of crayfish plague (Edgerton et al. 2004).

Disease monitoring often requires information on more than just parasite presence or abundance. Many reports of emerging freshwater infections are linked to at least one of invasive species, aquaculture intensification, nutrient and pollutant runoff or changing food web structure (Daszak et al. 2000; Johnson & Paull 2011). Policy changes and improved surveillance have been advocated to decrease the likelihood of pathogen introduction and maximize opportunities for control – with considerable potential to inform human disease management (*e.g.*, malaria, schistosomiasis, giardiasis, West Nile fever) (Steinmann et al. 2006). Where infections involve both wildlife and human hosts, or have parallels in transmission control, freshwater management to limit eutrophication, maintain higher trophic levels (*e.g.*, predators) and prevent invasive species could help regulate infections across a range of host taxa.

2.3.4 Harmful Algal Blooms

Freshwater algae occupy a pivotal trophic position, providing energy and nutrients to connected aquatic food webs. Periodically, and arguably more frequently, algal species are selected by environmental (bottom-up) or ecological (top-down) forces allowing for the accumulation of biomass. These conditions of accumulated biomass of algal species are termed harmful algal blooms (HABs). Often viewed as physiologically-simple organisms, investigation into the formation of HABs (D'Alelio et al. 2016) reveals that these organisms can occupy a plethora of niches, and these niches are open to native species that are in low concentrations in natural waters as well as to invasive species, with both contributing to HABs. Global changes have increased opportunities for algal species to become ecologically prevalent, contributing to the recent upsurge in HABs and include climate warming (Elliott 2012; Huisman et al. 2018), hydrological intensification (where dry areas become drier and wet areas become wetter, with increased frequency of intense precipitation events even in areas where precipitation decreases) (Huntington 2006; Trenberth 2011), eutrophication (Downing 2014) and brownification (Kritzberg & Ekström 2012). These physical changes in surface waters (*e.g.*, elevated and constant temperatures) enhance the growth of potentially harmful algae (Paerl & Huisman 2009), and provide the water column stratification required for photosynthetic prokaryotes to dominate and express toxicity (Burford et al. 2016). Furthermore, chemical changes in surface waters can select for species able to exploit the altered inorganic-organic matrices of iron and phosphorus (Kritzberg & Ekström 2012), significantly affecting the speciation of dominant algae, the distribution of primary producer dominance (pelagic *versus* benthic) and overall water quality through the production and release of select toxins (*e.g.*, microcystins) (Ekvall et al. 2013). The cumulative effects of these global changes result in greater complexity and uncertainty in our ability to predict the magnitude, frequency and duration of HAB events.

Once established, HABs threaten freshwater biodiversity. Some result in fish kills – either indirectly by reducing dissolved oxygen availability, or directly through toxin production. The bloom species create adverse physiological conditions for their competitors, altering energy or nutrient fluxes through food webs as they produce allelopathic or toxic compounds that reduce growth, survival and reproduction in other organisms or contaminate food webs. For example, the trophic transfer of cyanotoxins, the best studied group of freshwater toxins, into secondary and tertiary consumers leads to physiological and behavioral impairments (Ferrão-Filho & Kozlowsky-Suzuki 2011). Humans can also be exposed to cyanotoxins through inhalation of aerosolized toxins, ingestion of lake water or consumption of fish (Caller et al. 2009). One environmental toxin that has gained considerable attention is the amino acid β-N-methylamino-L-alanine (BMAA) (Brand et al. 2010; Merel et al. 2013). BMAA is a neurotoxin that has been identified as an emerging compound of concern because of its putative role in neurodegenerative illnesses (*e.g.*, amyotrophic lateral sclerosis and Alzheimer's disease) (Banack et al. 2015). BMAA biosynthesis is thought to be a ubiquitous trait shared among most genera of cyanobacteria (Cox et al. 2005) and can accumulate in aquatic food webs plagued by cyanoHABs (Brand et al. 2010; Jiao et al. 2014). Despite these findings, the lack of a universal protocol for quantifying BMAA and ambiguity surrounding the production of BMAA by cyanobacteria creates great uncertainty surrounding this topic (Faassen 2014).

Surveillance is needed to monitor the incidence of HAB-associated illnesses

(Backer et al. 2015). Coordinated national and international research agendas must develop effective HAB policies and management systems (Creed et al. 2016). Preventative measures include one or more of the following: reducing or removing external nutrient loads (Paerl et al. 2011); aerating lake sediments (Prepas et al. 1997); or chemically treating lake sediments to suppress internal nutrient recycling (Molot et al. 2014). Mitigation measures include chemical controls (*e.g.*, algicides or flocculants), physical controls (*e.g.*, increasing flows to reduce water residence time and remove cyanobacteria) and biological controls (*e.g.*, introducing organisms that consume HAB species) (Rastogi et al. 2015). Ultimately, managing HAB risks requires comprehensive analyses of the effectiveness and compliance of the entire management system, including hard controls that prevent pressures and impacts, as well as soft controls that enable, facilitate or track the effectiveness of hard controls.

2.3.5 Expanding Hydropower

Almost half (48%) of global river volume is altered by flow regulation and/or fragmentation (Grill et al. 2015). There are currently 3,700 major hydropower dams either planned or under construction, mostly in countries with emerging economies (Zarfl et al. 2015; Winemiller et al. 2016). Completion would cause 93% of all river volume to be affected by flow regulation and/or fragmentation (Grill et al. 2015), adding to the accumulating effects of existing dams on discharge, temperature, solutes, sediment transport and fish migration (Reidy Liermann et al. 2012; Pelicice et al. 2015). Hydropower dam construction endangers freshwater biodiversity as dams modify natural flow and thermal regimes and decrease river-floodplain connectivity, aquatic productivity and fish access to spawning and nursery habitats (Freeman et al. 2007; Juracek 2015). Even when hydropower projects involve fish passage structures to promote movement through dams, such structures may be ineffective (Pompeu et al. 2012) or even function as ecological traps (Pelicice & Agostinho 2008). Despite evolving viewpoints regarding the sustainability of large hydropower plants (LHPs), there has been a major increase in support for the widespread development of small hydropower plants (SHPs). Tens-of-thousands of SHPs are operating or are under construction (11 SHPs for every LHP) and this number is estimated to triple if all potential generation capacity were to be developed (Couto & Olden 2018). Fueled by considerable political and economic incentives in recent decades, the growth of SHPs has greatly outpaced available ecological science.

A major related concern is reservoir aging. Sediment imbalances associated with dam operation and tributary inputs cause reservoirs to 'age' through sedimentation, shoreline erosion, and channel degradation after time periods (*e.g.*, 50 years) that vary regionally (Juracek 2015). Sedimentation fragments aquatic habitats, impairs fish health and survival, decreases fish production, lowers primary production and reduces storage capacity. Altered waterfront access impairs the ability of reservoirs to support other human needs (*e.g.*, flood control, water supply, navigation) (Chapman et al. 2014; Juracek 2015). Many large-river impoundments are reaching 50+ years of age as they were built in the mid-twentieth century when political and economic conditions favored dam construction (Avakyan & Iakovleva 1998).

Fish harvest and food security of river-dependent peoples may also be impaired by hydropower, including proposed projects in large river systems such as the Amazon (Winemiller et al. 2016) and Mekong (Orr et al. 2012; Ziv et al. 2012) – basins with high fish biodiversity that historically had limited hydropower. In the Amazon, where there are now 154 large hydropower dams, completion of all 277 proposed dams would leave only three free-flowing tributaries and thereby threaten fish biodiversity, fish-based economies and food security (Pelicice et al. 2015). The lower Mekong, the world's largest inland capture fishery, is likewise jeopardized by dam construction along the river's mainstem (Ziv et al. 2012; Winemiller et al. 2016). In addition, flooding lands to create reservoirs increases the methylation of mercury and its transfer to fish, also affecting food security for communities (Bodaly et al. 2007). Reservoirs, particularly in the tropics and subtropics, are major sources of GHG emissions (Deemer et al. 2016) – hydropower offers a renewable but not climate-neutral energy source.

Shifting the food security of rural inhabitants from aquatic protein to land-based, livestock-derived protein presents considerable socioeconomic challenges, including the need for additional land and water for livestock operations (Orr et al. 2012). Potential interactions between hydropower development and other freshwater stressors (*e.g.*, climatic changes, land cover alterations) (Hermoso 2017), and associated effects on ecosystems and human populations, remain unclear. At present, hydropower projects are generally assessed on a site-specific basis that does not account for such interactions or potential environmental-socioeconomic tradeoffs (Orr et al. 2012; Winemiller et al. 2016). There is thus a need for comprehensive hydropower assessments that synthesize multiple potential impacts.

2.3.6 Emerging Contaminants

Surface waters receive pollution from point source discharges such as mining, agriculture and aquaculture, pulp and paper production, oil and gas production, and urban runoff. Each of these can impair freshwater biodiversity indirectly through impacts on habitat or through direct toxicity. However, because of environmental treaties such as the Stockholm Convention (2001), the global production and use of chemicals have shifted from persistent, bioaccumulative and toxic compounds, such as the insecticide dichlorodiphenyltrichloroethane (DDT), to pesticides and industrial chemicals with shorter environmental residence times and lower toxicities. In addition, with improved wastewater treatment across sectors (*e.g.*, municipal effluents) (Holeton et al. 2011), the focus in developed countries is less on addressing acute toxicity (*e.g.*, ammonia) and more on assessing and mitigating longer-term effects from both older, legacy and emerging contaminants. The latter is a broad, all-encompassing term that covers both newer substances or known contaminants for which there are newer concerns and includes, but is not limited to, active pharmaceutical ingredients, illicit drugs, personal care product additives, newer pesticides, endocrine disrupters, nanomaterials (see **Section 2.3.7** Engineered Nanomaterials) and microplastics (see **Section 2.3.8** Microplastic Pollution); all have garnered widespread attention because of their unexpected or unknown biological activity and/or stability (or pseudo-persistence) in aquatic environments. As an example, surveys of wastewater-impacted rivers show the global presence of pharmaceuticals such as antibiotics, antivirals and antidepressants, with antibiotics being the most frequently detected (Hughes et al. 2013). Yet, the effects of these individual compounds and their mixtures on aquatic populations and communities, as well as ecosystem function, remain understudied.

The endocrine-disrupting chemicals and, more specifically, the estrogen mimics are relatively well-understood with respect to their impacts on some aquatic species (Sumpter & Jobling 2013). Across taxa, fishes are most susceptible to the natural and synthetic hormones present in municipal effluents, with effects ranging from the production of vitellogenin and development of intersex in males (Jobling et al. 2002) to reduced abundances (Kidd et al. 2007). More recently, individual-level effects – specifically intersex – have been linked to transgenerational effects in offspring (Schwindt et al. 2014), reduced fitness (Harris et al. 2011) and potential declines in genetic diversity (Hamilton et al. 2016). Although these chemicals are of low risk for lower-trophic-level taxa, there is the potential for food-web-mediated effects on primary consumers through reduced predation pressure following declines in fish abundance (Kidd et al. 2014). The attendant risks to ecosystems are not yet clear.

Antimicrobial compounds, including antibiotics and personal care product additives, are found in municipal wastewaters and agricultural runoff. It is not surprising that chemicals designed to kill microorganisms in humans would also affect natural microbial communities (Barra Caracciolo et al. 2015). It was unexpected, however, that these contaminants (*e.g.*, triclosan) could affect algal diversity and periphyton, as well as some primary consumers (Nietch et al. 2013). More recent studies reveal effects of other emerging contaminants (*e.g.*, anti-inflammatories, antidepressants) on algal communities (Bácsi et al. 2016; Richmond et al. 2016). In addition to affecting species abundance and composition, antimicrobial compounds could also affect aquatic ecosystem function (Nietch et al. 2013), but downstream biodiversity implications are speculative.

Potential mitigation of emerging contaminants includes advanced treatment of municipal wastewaters and source reductions. Though outfall concentrations are sometimes reduced (*e.g.*, acetaminophen, estrogens) by more advanced treatment processes – and with subsequent benefits downstream (Hicks et al. 2017) – some emerging contaminants (carbazepine, triclosan and diclofenac) are more recalcitrant and require the development of novel interventions (*e.g.*, Bean et al. 2016). Source reductions are effective and necessary for some emerging contaminants given the lack of treatment options, and gains are being made (*e.g.*, reducing use of antibiotics in livestock production and microbeads in cosmetics in some jurisdictions). Reductions in human pharmaceutical usage are unlikely, but downstream gains and better protection of biodiversity could occur through both improved disposal of unused medications and advanced wastewater treatment.

2.3.7 Engineered Nanomaterials

Engineered nanomaterials (ENMs) are manufactured materials (size range 1–100 nm) used in a multitude of industrial, clinical and consumer applications (Stone et al. 2010). ENMs have exceptionally high surface area to volume ratios and often exhibit unique physical and chemical properties compared to conventional materials. While these characteristics make them desirable in a multitude of applications (Lee et al. 2010; Tong et al. 2014), they can also make ENM bioactivity difficult to predict. Large quantities are finding their way into fresh waters, but analytical limitations (von der Kammer et al. 2012) mean that current burden estimates are based primarily on models (Gottschalk et al. 2013; Sun et al. 2014; Dale et al. 2015). In rivers, predicted concentrations for common ENMs are in the ng/L range (or lower), with some formulations possibly reaching μg/L (Gottschalk et al. 2013). Many formulations are prone to aggregation and precipitation in natural waters, meaning epifaunal and infaunal organisms will be exposed to ENM concentrations orders of magnitude higher than pelagic species in the same system (Selck et al. 2016). Specific estimates of freshwater sediment concentrations are unavailable, but for surface waters in general they are likely in the μg/kg range and will increase with continued growth of the nanotechnology industry (Gottschalk et al. 2013).

Predicted environmental burdens are generally well below toxicity thresholds for common ENMs (Coll et al. 2016), but data on pelagic species are over-represented, so the overall risk may be considerably higher (Selck et al. 2016). It is not uncommon to observe minimal acute toxicity of pristine (*i.e.*, as manufactured) ENMs in freshwater fish and crustaceans at realistic exposure concentrations, but sensitivity can vary by orders of magnitude across species and life stages (Callaghan & MacCormack 2017). With size as the primary classifier, ENMs can be composed of a variety of organic, inorganic or composite materials, so generalizations about their global safety for freshwater organisms is difficult (Coll et al. 2016).

Core materials are often 'functionalized' with surface coatings to suit specific applications, and changing this coating can increase ENM bioavailability and/or bioactivity by orders of magnitude (Osborne et al. 2013). Many emerging nanotechnology industries are exploiting this 'tunability' to create next generation products with the potential for significant effects on fresh waters. Nano-pharmaceuticals are an area of intense growth, and the introduction of ENM-enabled drugs or drug delivery systems into fresh waters warrants careful consideration (Berkner et al. 2016). Agricultural applications, including fertilizers, herbicides and pesticides (Wang et al. 2016), are also a concern. While improvements in targeting and efficacy over conventional chemicals could greatly reduce the total mass of product applied, the increased potency and unique ENM-related properties of these products may introduce new problems once they eventually reach fresh waters. For example, formulations specifically designed to carry bioactive agents may enhance the availability and toxicity of existing environmental contaminants by acting as a 'Trojan horse' (Boncel et al. 2015).

A major barrier to understanding the risks of emerging ENMs is the lack of sufficient detection and characterization technologies (von der Kammer et al. 2012; Coll et al. 2016). Current models require more detailed inputs to accurately estimate ENM burdens and predict risks to freshwater ecosystems. Variations in ENM structure (*e.g.*, similar core materials with different coatings) and key parameters like water chemistry, ENM weathering, dissolution and aggregation kinetics can greatly impact particle fate and bioactivity (Peijnenburg et al. 2015) and are not accounted for in current models. Most available bioactivity data again derive from acute studies on pelagic species, and there is still considerable uncertainty about long-term risks from even the most common ENMs (*e.g.*, titanium dioxide, zinc oxide, silver). The additional variability in reported sensitivity ranges and the absence of trends in toxicity mechanisms across taxa (Gottschalk et al. 2013) underscores the need for caution when developing strategies for managing the use and disposal of novel ENMs.

2.3.8 Microplastic Pollution

Globally, annual plastic production has reached over 400 million tons (Geyer et al. 2017) for products designed to be inexpensive and disposable. Rather than biodegrading, plastics are broken down by mechanical forces and UV radiation into smaller fragments (Barnes et al. 2009) called 'microplastics' (plastic particles <5 mm). Microplastics include microbeads (particles added to cosmetics), nurdles (small pellets used to produce other plastics), fragments (portions of larger pieces) and microfibers (from synthetic clothing) (Browne et al. 2011). In marine environments, microplastics have negative environmental impacts, such as concentrating contaminants and ingestion by animals, which reduces fitness and increases mortality (Sigler 2014; Provencher et al. 2015). Although data on freshwater microplastic concentrations are limited, microplastic pollution in freshwater ecosystems is now being reported (reviewed in Eerkes-Medrano et al. 2015), including the Laurentian Great Lakes (Eriksen et al. 2013), the St. Lawrence (Castañeda et al. 2014), the Danube (Lechner et al. 2014) and other river systems that form a plastic conduit between land and sea. In some years, microplastic concentrations in the Danube River can outnumber planktonic larval fish concentrations (Lechner et al. 2014). Microplastic pollutants vary among freshwater systems, but microfibers often comprise >75% of the plastic debris (Ballent et al. 2016; Vermaire et al. 2017). Derived from washing synthetic clothing (Browne et al. 2011), the release of these microfibres is difficult to control in existing municipal wastewater treatment but filters on washing machines may be an option. Microplastics are also deposited in aquatic sediments and benthic habitats (Castañeda et al. 2014; Ballent et al. 2016; Vermaire et al. 2017), exposing benthic organisms.

Microplastics are ingested by freshwater organisms including birds (Holland et al. 2016), fishes (Campbell et al. 2017) and invertebrates (Windsor et al. 2019) and extrapolation from marine findings would suggest emerging risks to freshwater organisms (Sigler 2014; Provencher et al. 2015). Better management of microplastic pollution in fresh waters requires a clearer understanding of: (i) sources, sinks and fluxes; (ii) factors controlling spatio-temporal variations in microplastic concentrations; (iii) data on co-transported contaminants; and (iv) routes of uptake and effects on freshwater organisms (Wagner et al. 2014). Legislation to control microbeads has been implemented in several countries (United States: Microbead-Free Waters Act 2015; Canada: Microbeads in Toiletries Regulations 2016), but these typically represent only a small fraction of the total plastic pollution (Ballent et al. 2016; Vermaire et al. 2017). As plastic production and consumption increase without better control, plastic concentrations in fresh waters are likely to rise. Improved understanding of their fate and impact is therefore a priority. In sum, the science supporting mitigation of emerging contaminants such as microplastics and ENMs lags behind that of the pharmaceuticals and personal care products. Further research is required on what impacts, if any, these materials are having on freshwater ecosystems.

2.3.9 Light and Noise

Contemporary civilization relies on electricity and combustion engines – often sources of light (Longcore & Rich 2004) and noise (Kight & Swaddle 2011). Although well-documented in terrestrial systems, most aquatic research has been marine-focused with relatively little effort in fresh waters even though lit road networks, urban development and industrial infrastructure are frequently co-located along rivers and lakes (Gaston et al. 2014).

Light pollution is increasingly regarded as an insidious stressor for freshwater biodiversity (Hölker et al. 2010). Early studies revealed that artificial light alters the diel vertical migration of the zooplankter *Daphnia* (Moore et al. 2000), potentially altering their interactions with fish. Recently, (Hölker et al. 2015) revealed that even microbial communities can be affected by artificial light at night (ALAN), potentially transforming freshwater systems into nocturnal carbon sinks. Light also alters the behaviour of organisms often closely attuned to circadian cycles and, for example, ALAN can mediate interactions between invasive signal crayfish (*Pacifastacus leniusculus*) and native species (Thomas et al. 2016a). For fish, (Foster et al. 2016) revealed how light pollution increased energy expenditure of nesting smallmouth bass (*Micropterus dolomieu*) during the parental care period. Street lighting also delays dispersal in juvenile Atlantic salmon (*Salmo salar*), and this effect increased with lighting intensity (Riley et al. 2013, 2015). While most research has focused on individuals, the potential for system-level changes is clear given the importance of light as a cue to processes such as invertebrate drift and feeding by drift-feeding fishes.

The effects of noise in fresh water were first revealed for waterbirds disturbed by aircraft and boats (Ortega 2012), but Zhang et al. (2013) subsequently showed that noise from trucks disturbed endangered black-faced spoonbills (*Platalea minor*) in the Pearl River wetlands of China. Motorboat noise can reduce the extent of basking among freshwater turtles (Jain-Schlaepfer et al. 2017), lowering body temperature and influencing energy assimilation. Traffic and aircraft noise have also affected anurans (Tennessen et al. 2014), for example, impeding the ability of frogs to communicate (*e.g.*, changing the spectral frequency used and frequency of calling) during breeding (Kruger & Du Preez

2016). Interestingly, Bleach et al. (2015) revealed that noise generated by invasive cane toads (*Rhinella marina*) impeded the calling behaviour of native Australian frogs. Recent research revealed that boat noise elevates the stress hormone cortisol (Wysocki et al. 2006) and increases metabolic expenditure (Graham & Cooke 2008) while reducing foraging performance (Purser & Radford 2011) and antipredator behaviours (Simpson et al. 2015) in freshwater fish. How these disturbances scale up to ecosystem-level effects is unknown, although noise can alter how sediment-dwelling invertebrates affect ecosystem properties (Solan et al. 2016).

For future management, we suggest that there may be opportunities to identify specific light types, lighting regimes or spectra that are less deleterious to aquatic biodiversity. The education of communities and regional governments as typical stewards of lighting regimes (*e.g.*, on roads, docks, bridges) will also be fruitful. Noise pollution mitigation has perhaps been best developed for boats and has taken the form of motor restrictions (*e.g.*, no combustion motor zones or speed zones) as well as innovations in motor design that reduce noise outputs. But there is still much to do to abate other forms of noise.

2.3.10 Freshwater Salinisation

Regional studies suggest that freshwater salinisation is occurring at an unprecedented rate and scale (Herbert et al. 2015), but there remains no global synthesis of this problem. The threat posed by salinisation is far from new, but it is predicted to intensify with climate change. Estimates suggest that 1.5×10^8 ha of forest and wetlands are salt-affected worldwide (Wicke et al. 2011), and 1.5×10^7 ha of freshwater peatlands are vulnerable to sea-level rise (Henman & Poulter 2008). Vegetation clearance allows for greater accessions of rainfall to groundwater via recharge zones. This imbalance increases hydrostatic pressure in lowland aquifers increasing discharge from saline water tables driving dryland salinisation. The semi-arid zones that are vulnerable to salinisation may experience less rainfall under warming scenarios, mitigating the rise in water tables, yet reduced runoff may lead to increased concentration of salts in surface waters (Mills et al. 2013). Irrigation salinisation arises from the direct application of waters to agricultural lands. These are usually more saline than rainfall, and the salts evapoconcentrate even from the application of very dilute waters, leading to salinised surface soils. In warmer, drier climates, evaporation rates may increase with climate change, and greater volumes of water are likely to be applied to avoid crop desiccation (Vörösmarty et al. 2010). While technologies emerging under precision agriculture may make water application more efficient, increased developing-world populations will likely adopt low-technology irrigation agriculture, expanding the extent of fresh water at risk.

The proliferation of large impoundments on major rivers (Zarfl et al. 2015), as well as many thousands of smaller dams and the dense matrix of artificial waterpoints in agricultural landscapes, combine to limit the flow of freshwater runoff to coastal zones. Reduced flow also limits the dilution and flushing of tidal waters, raising their salinity. Many salinising coastal zones are under threat from rising sea levels which are likely to inundate lowland systems (Henman & Poulter 2008). This will be compounded by the increasing exploitation of fresh groundwater resources and the increasing frequency of hurricanes and storm surges (*e.g.*, Schuerch et al. 2013). Other anthropogenic drivers of freshwater salinisation include: disposal or accidental spillage of saline waste water from the production of coal seam gas and shale oil (Vengosh et al. 2014); strip mining of oil sands which exposes marine sediments and shallow saline aquifers (Gibson et al. 2013); and the expanding use of salt to de-ice impervious surfaces (Findlay & Kelly 2011; Kaushal et al. 2018).

Biological effects of salinisation include the continued replacement of salt-intolerant taxa with those that can withstand elevated concentrations (Radke et al. 2003). Increased salinity kills freshwater species owing to toxic levels of sodium and chloride ions in their cells and reduced capacity to take in essential ions and water. These effects can reduce species diversity and significantly alter trophic systems by reducing food sources for consumers (Finlayson et al. 2013). While freshwater plants can withstand short intervals of increased salinity, sustained periods can lead to reduced productivity and threaten the viability of rhizomes and stored seeds. Salinisation can induce density stratification rendering surface sediments anoxic, leading to regime shifts in freshwater plant communities (Davis et al. 2010). The growth, fecundity and diversity of freshwater invertebrates is also known to decline with rising salinity (Pinder et al. 2005). Many vertebrates are also impacted, often *via* indirect effects such as habitat and food web changes, however anurans are particularly sensitive, especially juvenile stages (Smith et al. 2007). Mitigation of salinisation may include controlling the release of salts from point sources or pumping aquifers to lower water tables, but these tend to be local in scale. The strategic release of freshening flow can be effective at a more regional scale but can come at a considerable cost, including the cost of not using that water for environmental or consumptive purposes (Herbert et al. 2015).

2.3.11 Declining Calcium

Most aquatic environmental threats are related to the excess of a limiting nutrient (*i.e.*, eutrophication) or a chemical contaminant that exceeds safe concentrations. In contrast, relatively few anthropogenic stressors are related to diminishing supplies of limiting nutrients. One example of a recently identified threat is the slow but widespread decline in calcium (Ca) concentrations in low carbonate systems across eastern North America (Likens et al. 1998; Keller et al. 2001; Molot & Dillon 2008), Europe (Stoddard et al. 1999; Skjelkvåle et al. 2005; Hessen et al. 2017), and likely elsewhere. Ca is an essential nutrient for all forms of life, but the ecological ramifications of this new threat are still not fully understood.

Although Ca-rich dust may play a role (Hedin et al. 1994), the principal source of Ca to freshwaters is the slow weathering of parent bedrock that supplies the Ca pool within catchment soils, which is then potentially available for export to lakes and rivers. Growing evidence shows that human activities have disrupted the Ca cycle of many softwater lakes, reducing the supply of Ca and lowering aqueous Ca concentrations below the demands of some aquatic organisms through two major processes (Jeziorski & Smol 2017). First, acid rain accelerated the leaching of Ca into lakes, and so, for a period of time lake-water Ca concentrations were likely elevated. In areas with geology characterized by high Ca concentrations (*e.g.*, limestone bedrock), Ca continued to be easily leached into waterways. However, in many low-Ca regions, such as those underlain by Precambrian granitic bedrock, Ca supplies were eventually depleted, as the maintenance of suitable concentrations is mainly dependent on slow weathering processes. Second, as large amounts of Ca are bound up in timber, forestry practices can act as a net export of some of the catchment's Ca reserves, exacerbating watershed Ca loss (Allen et al. 1997; Watmough et al. 2003).

Identifying the ecological effects of long-term Ca declines has, thus far, primarily focused on the Cladocera, often a dominant and keystone group of lake invertebrates. Early analyses revealed that some large bodied cladocerans (*e.g.*, some *Daphnia* spp.) have relatively high Ca requirements (Jeziorski & Yan 2006; Ashforth & Yan 2008), with some populations unable to persist should, for example, ambient Ca concentrations fall below 1.5 mg/L. Given that monitoring programs were already recording lower Ca concentrations in many softwater lake regions, concerns were raised that this environmental threat may be affecting lake foodwebs. A common thread is that Ca declines have been slow and gradual, requiring either paleolimnological (Jeziorski et al. 2008) or long-term monitoring data on the order of decades to identify the problem (Molot & Dillon 2008). For these reasons, Jeziorski et al. (2008) used analyses of fossil Cladocera to show that, indeed, major shifts in invertebrate assemblages could be linked to declining Ca levels. They found that many softwater lakes were already showing signs of Ca depletion with concomitant changes in cladoceran assemblages. Furthermore, the paleolimnological data indicated that the recent declines in Ca concentrations recorded in the lake monitoring programs were not simply a trend of Ca levels rebounding to pre-acidification levels (as one would have expected higher concentrations of Ca in lakes during the early periods of lake acidification), but that current Ca levels were now lower than pre-acidification concentrations. Paleolimnologists reached this conclusion because Ca-sensitive *Daphnia* taxa were often common in the pre-acidification fossil record, indicating that Ca levels were sufficiently high prior to acidification. Subsequent studies confirmed this overall trend in a spectrum of softwater lake ecosystems, which may also impact other groups of freshwater biota that have high Ca requirements (reviewed in Jeziorski & Smol 2017), such as crayfish (Hadley et al. 2015).

Although the study of declining Ca was initially focused on taxa impacted by reduced Ca availability (*e.g.*, large-bodied *Daphnia*), subsequent research has begun to center on organisms that may benefit from this new threat. For example, given that large *Daphnia* are efficient filter feeders, their demise may be linked to recent algal blooms, due to reduced top-down effects (Korosi et al. 2012). In addition, Jeziorski et al. (2015) documented the widespread replacement of *Daphnia* with *Holopedium glacialis*, a jelly-clad competitor with low Ca requirements. Although both are filter-feeding planktivores, *Holopedium* have lower nutrient content than *Daphnia* and high concentrations of the jelly-clad *Holopedium* can disrupt water filtration equipment. The ensuing "jellification of lakes" is a new problem which potentially can cascade through the food web.

The solution to the threat of Ca declines is not a simple one given the large number of affected lakes and their typically remote locations. Further reductions in acidic precipitation is potentially a long-term solution, although one with significant economic repercussions. On a smaller scale, some local attempts have been initiated to replenish Ca in watersheds by, for example, "fertilizing" with Ca-rich wood ash (*e.g.*, Haliburton, Ontario, Canada). The efficacy of these pilot projects has not yet been evaluated.

2.3.12 Cumulative Stressors

Although there is long-standing recognition that environmental stressors can interact to affect freshwater ecosystems, the last decade has seen considerable growth in interest in potential ‘multiple stressor’ problems (Ormerod et al. 2010; Vörösmarty et al. 2010; Craig et al. 2017). The first of three key reasons is the increasing appropriation of freshwater resources for human use coupled with growing downstream impacts from human activities (Strayer & Dudgeon 2010). Second, human effects on fresh waters often occur in combination, either because different activities coincide (*e.g.*, urbanization with industry; agriculture with abstraction; biomass exploitation with invasive species release) or because they affect freshwater ecosystems through multiple pathways. Third, climate change is expected to have widespread direct and indirect effects on fresh waters (see **Section 2.3.1** Changing Climates). In this growing area of interest, there are three linked and prominent challenges.

First is the need to resolve whether multiple freshwater stressors simply co-occur, or whether they have interacting effects. Early experimental evidence suggested that some stressor combinations could be synergistic (*e.g.*, high temperature *x* toxic stress), but in most cases stressor combinations were less-than-additive (Folt et al. 1999). These patterns have been largely borne out by recent meta-analysis, where the net effects of dual stressors on biological diversity and ecosystem function appeared to be dominantly additive and antagonistic, respectively (Jackson et al. 2016b). Data from 88 papers and almost 300 stressor combinations revealed interactions were most commonly antagonistic (41%), rather than synergistic (28%), additive (16%) or reversing (15%). This variation among outcomes suggests a need to understand the exact contextual factors that influence stressor interactions. Ecosystems or organisms of high conservation importance are often characterized by specific requirements that might be disproportionately sensitive to some stressor combinations. Furthermore, biodiversity erosion might increase multiple stressor impacts as ecosystem functions are impaired or sensitivities change. For example, (Vinebrooke et al. 2004) illustrated how lake community composition could reduce or increase combined stressor response depending on the extent to which species shared stress tolerance. In some cases, multiple stressor effects on fresh waters have led to unexpected 'ecological surprises' through non-linear or delayed interactions in systems that were otherwise well understood (Hecky et al. 2010).

A second challenge is to develop methods for diagnosing the relative importance of stressors with combinatorial effects. A possible explanation for the dominance of antagonistic interactions is that those with a large impact might mask or override the effects of lessor stressors (Jackson et al. 2016b). Under these circumstances, removing a dominant stressor might simply reveal the effects of other stressors without a net biodiversity gain. In contrast, identifying any hierarchical effects of co-occurring stressors could help target sequential approaches to management and lead to tangible biodiversity gains (Kelly et al. 2017). Thus far, reliable evidence and case studies from which to develop generalizable best practices are limited, and often based on data analytical approaches to prevailing stressor combinations that might not represent the effects of sequential stressor management (Gieswein et al. 2017).

Against this uncertain background, a third challenge is to identify pragmatic approaches to managing multiple stressor impacts. The largest benefits would be likely where multi-purpose solutions tackle multiple problems simultaneously – most straightforwardly by prioritizing resource protection over exploitation in catchments or water bodies identified for biodiversity importance (*e.g.*, EU Habitats Directive 92/43/EEC; see **Section 2.5** Is There Hope For Conserving Freshwater Ecosystems?).

Riparian solutions offer a smaller-scale alternative, for example, where 'buffer zones' simultaneously influence water quality, protect thermal regimes, provide habitat structure and maintain energetic subsidies, although they are not equally effective for all pollutants (Lowrance et al. 1997). Overall, however, there is a pressing need to understand and address multiple stressor problems, particularly their impacts on freshwater biodiversity.

2.4 Conservation and Management Tools

Despite the overall grim prognosis for freshwater biodiversity, there are opportunities for conservation action and effective management. Emerging tools and technologies (see **Section 2.4.1** Environmental DNA and **Section 2.4.2** Environmental Flows) will be essential in mitigating some emerging threats (see Jackson et al. 2016a). Some existing approaches (see **Section 2.4.3** Aliens and Aquaculture, **Section 2.4.4** Fishways and Dam Removal and **Section 2.4.5** Climate Change and Managed Relocation of Species) could also help support biodiversity conservation while meeting human needs; these, however, have been met with varying levels of success, yet offer insight into the effectiveness of different freshwater conservation strategies. In this section, we present a short-list of tools and techniques that have relevance to freshwater conservation either in their previously established or potential future uses and reflect the expertise of the author group.

2.4.1 Environmental DNA

Deoxyribonucleic acid (DNA) from lake, wetland and river organisms is present in the water column as secretions, cells, tissues, feces or gametes, and is transported through drainage networks. Fragments of this environmental DNA (eDNA) can be isolated from organic matter in water samples, sequenced and assigned to known species using metabarcoding (Elbrecht & Leese 2017). The potential conservation applications of eDNA techniques are substantial in detecting rare and endangered freshwater species whose presence cannot be confirmed easily by more conventional means (Jerde et al. 2013; Laramie et al. 2015; Eva et al. 2016), and for monitoring the colonization of new habitat by potentially invasive species or pathogens (Rees et al. 2014). This targeted or 'active' surveillance directed towards detection of eDNA for a single species of interest can be contrasted with 'passive' surveillance, using high-throughput sequencing, whereby sampled eDNA is used to assess community composition and opportunistically reveals the presence of a species of interest (Simmons et al. 2016). The latter approach also has potential applications for bioassessment, since the eDNA signal of a community of macroinvertebrates could be used to estimate diversity with less investment of time and effort than the benthic sampling methods that are widely used currently (Rees et al. 2014; Elbrecht & Leese 2017). Wider application of eDNA techniques will certainly not be a panacea that can replace the requirement for taxonomic expertise about freshwater biota, nor are such approaches (yet) able to provide reliable quantitative information about population sizes of species of interest. Nonetheless, when combined with next-generation sequencing methods, collection of eDNA transported in river networks offers a spatially-integrated way to assess the species richness (both aquatic and terrestrial) of entire drainage basins, and could well transform biodiversity data acquisition in future (Deiner et al. 2016).

2.4.2 Environmental Flows

One approach to mitigating the effect of flow regulation on fresh waters is the practice of water allocations (environmental flows, or e-flows) to protect or restore ecosystems. The scientific consensus is that e-flows should provide water levels or discharges that mimic natural hydrologic variability and incorporate a range of flows essential to support functioning ecosystems (Arthington et al. 2018). By accounting for the variability of hydrographs, e-flows permit connectedness longitudinally along rivers and laterally with floodplains; this is vital in allowing adaptive responses by the riverine biota to the challenges of living in a warmer world, permitting movement among potential refugia as conditions change.

E-flows have stimulated much research into the question 'how much water does a river (or stream, or wetland) need'? A one-size-fits-all water allocation for river basins is theoretically possible globally (for example, 37% of mean annual flow) (Pastor et al. 2014), but such 'rules of thumb' are unlikely to capture all ecologically-important aspects of flow variability. Instead, the success of river protection and restoration will depend upon accurately modeling relationships between hydrological patterns and ecological responses, followed by implementation of water allocations within a range set by the resilience of these ecosystems (Poff & Zimmerman 2010). The accumulation of long-term hydrologic data is needed to evaluate hydroclimatic trends, to quantify flow regime alteration and associated flow-ecology relationships, and to design and implement e-flows prescriptions; current trends in streamgaging data coverage across the world is not encouraging (Ruhi et al. 2018).

Broad consensus has emerged among e-flow practitioners about how this can be achieved through the Ecological Limits of Hydrologic Alteration (ELOHA) approach to determine regionally-relevant hydro-ecological models and water allocations (Poff et al. 2010). In the many parts of the world where data explicitly linking hydrological changes to ecological responses are scarce, e-flow allocations will have to be based on whatever limited data can be deployed for the ELOHA approach, supplemented by best professional judgment and risk assessment. Under such circumstances, an e-flow allocation can be treated as a hypothesis-driven experiment in ecological restoration, with the outcomes monitored, evaluated and refined. Outcome analysis should be essential in any management intervention: a meta-analysis by Palmer et al. (2010) revealed shortcomings in the widely-used 'if you build it, they will come' approach of restoring physical habitat and flows in rivers if other stressors continue to limit ecological recovery. Such failures are frequent given that many freshwater habitats are subject to multiple interacting stressors (Craig et al. 2017).

2.4.3 Aliens and Aquaculture

Invasive species have inflicted profoundly damaging effects on recipient freshwater ecosystems; this is a fact (Gallardo et al. 2016). However, it must not be ignored that some non-native species can now play important ecological roles in human-altered environments, such as supporting lake food webs (Twardochleb & Olden 2016) and riverine ecosystem functions (Moore & Olden 2017). Species have been repeatedly and deliberately introduced outside their native ranges with the aim to support food security, recreation opportunities and ecosystem rehabilitation. Where the preservation of near-pristine freshwater environments is no longer a realistic option, the prospect of enhancing ecosystem-services through introduced alien species may become an option – and has clear parallels in terrestrial agriculture. Human livelihoods are a paramount consideration in parts of Asia, Africa and South America, irrespective of conservation concerns, whereas the need to protect native biodiversity has a stronger bearing on decisions in North America and Europe, where dependence on freshwater artisanal fisheries is generally lower. Some have argued that alien species could, under certain circumstances (*e.g.*, Gozlan 2008), contribute to conservation goals by providing habitat or performing desirable ecosystem functions (Schlaepfer et al. 2011). Even notorious invaders such as dreissenid mussels may provide lake management benefits through filtering activity and control of algal blooms (McLaughlan & Aldridge 2013). However, others strongly disagree (Vitule et al. 2012), arguing that the risks of alien introductions outweigh any beneficial roles they might play in enhancing ecosystem services. For instance, the ecological and economic damage caused by dreissenid mussels (Nakano & Strayer 2014) is not offset by the filtering service benefit provisioned by these biofouling animals.

Global declines in freshwater capture fisheries (Youn et al. 2014) will boost the case for expanding aquaculture – based often on introduced or potentially invasive species – to meet the shortfall in wild yields to support an ever-increasing human population. Decreasing natural production of freshwater fishes (relative to aquaculture) is a matter of great concern given that it provides the equivalent of all dietary animal protein for 158 million people, with poor and malnourished populations particularly reliant on these fisheries compared with marine or aquaculture sources (McIntyre et al. 2016). Freshwater fishery yields have consistently been underestimated (FAO 2016; Fluet-Chouinard et al. 2018), and their global importance underappreciated (Lynch et al. 2017; Reid et al. 2017). At least 21 million people engage regularly in freshwater fisheries (over a third of the global total for capture fisheries) and most are small-scale operators concentrated in Asia and, secondarily, Africa (FAO 2016). Many more, particularly women, engage in subsistence fishing with the catch contributing to family welfare. Such practices could not easily be replaced by aquaculture.

Aquaculture can lead to the proliferation of parasites, diseases and species introductions, as well as contaminating receiving waters with wastes and pharmaceuticals associated with intensive fish farming (FAO 2016). Putting these disadvantages aside, cultured fishes may not be an adequate substitute for capture fisheries. Wild fishes are more nutritious (higher protein and micronutrient content) than farmed individuals, even within species (Youn et al. 2014); thus, a switch to consumption of such fish as wild catches decline (assuming that were practicable) would result in poorer diets. Furthermore, a spatial coincidence between productive freshwater fisheries and low food security (McIntyre et al. 2016), as well as between per capita inland catch and extreme poverty (Lynch et al. 2017), highlights the crucial role of rivers and lakes in providing locally-sourced, low-cost protein and micronutrients. While further development of aquaculture might substitute for some food needs, it would be far better to secure provisioning of this ecosystem service by protecting these fisheries and the habitats that sustain them, for their own right (Dudgeon 2014), but also given the apparent correlation between biodiversity and stable, high-yielding fisheries (Brooks et al. 2016). The need to ensure that freshwater capture fisheries are fully considered in decisions about water-resource management will require that their contribution to food security is reliably assessed, valued and communicated to decision-makers and the public.

2.4.4 Fishways and Dam Removal

Research on devices that enable fish to traverse dams (in both directions) is needed urgently, as many dams are lacking such facilities or they have installed structures that fail to adequately pass focal species – typically salmonids – or the broader fish community (Pelicice et al. 2015). Indeed, some well-respected fish ecologists regard fishways as a failed technology that does not provide adequate passage – even for focal species – despite decades of use (Brown et al. 2013). Assessments of the effectiveness of different fishway designs and types to facilitate passage for representative species of migratory fish is urgently needed, especially in the tropics (Silva et al. 2018). Such targeted research might pay conservation dividends as the results could be applied readily. A range of stream types needs to be assessed to identify the most effective design for multispecies fishways (*e.g.*, Steffensen et al. 2013; Yoon et al. 2015), but one obvious generalization is that, irrespective of design details and ecological context, fishway effectiveness is inversely proportional to dam height. Some success in re-establishing fish migration has been reported for brown trout (*Salmo trutta*) (Calles & Greenberg 2009), Atlantic salmon (Nyqvist et al. 2017) and Macquarie perch (*Macquaria australasica*) (Broadhurst et al. 2013) – yet results have been mixed for other species despite targeted research to inform fishway design and operation (Baumgartner et al. 2014).

Even for those species they respond well to fishways, such structures are no more than a partial solution to the obstacles presented by dams, as the associated reservoirs are also a barrier to migration – especially in a downstream direction (Pelicice et al. 2015). Furthermore, they do little or nothing to alleviate the effects of dams and reservoirs on non-fishes, such as migratory shrimp (Holmquist et al. 1998). The only known technical solution is to open or completely remove dams. More than 1,200 dams have been removed in US in the last 40 years, and the decadal rate of removal is increasing exponentially (Bellmore et al. 2015). Such events are often spurred by the hazards posed by aging infrastructure but can result in conservation gains where migration routes are reestablished. Larger dams are becoming subject to attention, with the largest being the 2014 removal of the Glines Canyon Dam (64 m tall) from the Elwah River. Rivers respond quickly to dam removal, eroding and redistributing sediment and returning to pre-impoundment conditions within years, rather than decades (O'Connor et al. 2015). Ecological recovery is slower but nonetheless fairly rapid, and salmonids and other migratory fishes readily colonize newly-available habitat upstream (Grant & Lewis 2015). While rates of dam construction – especially large ones – far outpace the number of removals (Bellmore et al. 2015), the practice has momentum: in 2016, the governments of California and Oregon announced plans to remove four hydropower dams on the Klamath River as part of an effort to restore salmon fisheries.

2.4.5 Climate Change and Managed Relocation of Species

The rapidity of climate change is predicted to exceed the ability of many freshwater species to adapt or to disperse to more climatically favorable surroundings (Brook et al. 2008; Loarie et al. 2009). Conservation of these species may require managed relocation (also called assisted migration or assisted colonization) of individuals to locations where the probability of their future persistence is likely to be high, but where the species is not known to have occurred previously (Olden et al. 2011). Yet, there is good reason to question whether managed relocation is a viable conservation strategy. For example, managed relocation promotes the distributional expansion of species and thus may have undesirable effects on other species or ecological processes (Ricciardi & Simberloff 2009). Decisions regarding the managed relocation of freshwater species are clearly complicated. Quite simply, the effects of introducing a freshwater species to a new location are uncertain (and potentially disastrous), therefore the need for managed relocation must be balanced against the probability of species loss associated with doing nothing (Olden et al. 2011).

2.5 Is There Hope For Conserving Freshwater Ecosystems?

Current rates of extinction, habitat degradation and emerging challenges show that freshwater ecosystems already face pressures larger than any other ecosystem, and threats will intensify in future as the exploitation of freshwater resources grows to meet human demand. Conservation scientists working in freshwater ecosystems, therefore, have potentially important roles in providing evidence for actions to arrest decline, and to protect or restore the world's lakes, reservoirs, rivers, streams and wetlands. Here we highlight positive actions that illustrate potential options across scales, from local to global. The mechanisms vary, but they include legal regulation, fiscal incentives, market opportunities and voluntary action by learned or civil society, or ideally some combination of these drivers.

In Europe, regulatory instruments range from aiming to achieve good qualitative and quantitative status of all water bodies (*e.g.*, The Water Framework Directive 2000/60/EC) through to protecting specific freshwater ecosystems to support target taxa (*e.g.*, The Habitats Directive 92/43/EEC), for which there is evidence of opportunity. For example, the European Union Urban Waste Water Treatment Directive (91/271/EEC) led to extensive and long-term ecosystem recovery in urban rivers that were once among the world's most grossly polluted (Vaughan & Ormerod 2012). Continental-scale regulation has also contributed to the recovery of formerly acidified lakes and rivers ranging from local (*e.g.*, Sudbury, Ontario, Canada) to more extensive areas of Europe and North America – though in these cases biological responses have yet to fully match chemical trends (Kowalik et al. 2007; Ormerod & Durance 2009; Labaj et al. 2015).

Fiscal incentives are sometimes used by governments to protect water courses in otherwise intensifying agricultural systems using agri-environment schemes (AES). Examples include: riparian buffer zones to reduce nutrient flux; conservation easements in the US; and various forms of catchment-sensitive farming with reduced agro-chemical use or livestock density. Although promising for some pollutants (Zhang et al. 2010), comprehensive data are needed to illustrate wider success in tackling multiple stressors sufficiently to engender whole ecosystem recovery, including that of biodiversity.

Beyond government support, market mechanisms are increasingly considered as a means of managing freshwater catchments – specifically through natural capital accounting and markets for ecosystem services (Ormerod 2014). The basic concept is to protect catchments as a 'first line of defence' or as units of production for natural services from which financial gains can then flow. Investments are typically made to protect soil carbon, maintain runoff, regulate water quality or provide natural flood management, thus providing a financial return, for example, in tradeable water supply, reduced water treatment costs or reduced need for traditional engineered infrastructure. Biodiversity is protected either collaterally, or because organisms have a key role in ecosystem service delivery (Durance et al. 2016). Although this utilitarian view of natural systems is sometimes criticized, recognition of the role of freshwater ecosystems in human life support – as in the planetary health movement – may be an essential step towards their long-term protection. Key needs are to motivate investors, to move beyond small-scale demonstration projects and to ensure that conservation gains can be guaranteed to outweigh the risks of some resource exploitation implied in some forms of this paradigm.

Members of society and, in particular, non-governmental organisations (NGOs) act as important sources of lobbying, hope and demonstration in freshwater conservation. At a global scale, for example, the 2007 Brisbane Declaration at the Environmental Flows Conference, revised at the 2017 International River Symposium (Arthington et al. 2018), emphasized the ecosystem service role of fresh waters and called on governments, development banks, donors, river basin organizations, NGOs, community-based organizations, research institutions and the global private sector to take a range of actions to restore and maintain e-flows (Olden et al. 2014). The effectiveness of this call to action, however, remains to be assessed. Indeed, e-flow requirements have yet to be adequately assessed for most aquatic ecosystems and have been implemented in even fewer. There is still no comprehensive global record of e-flow implementations, nor a good understanding of why some projects have succeeded, while other initiatives have failed to materialize. Major obstacles to e-flow implementation lie largely outside the realm of ecology. They include a lack of political will and public support; constraints on resources, knowledge and local capacity; and institutional barriers and conflicts of interest (Arthington et al. 2018). These are matters of particular concern as a global boom in construction of hydropower dams is underway (Zarfl et al. 2015; Winemiller et al. 2016; Couto & Olden 2018), and demands for water continue to grow, especially in arid regions, or those experiencing shortages as a result of climate change.

Civil society action has also been instrumental in dam removal – particularly in North America – to restore river systems through improved longitudinal connectivity. As mentioned, over 1,200 dams have now been removed, but evaluations of effects are still scarce or short-term, and there is thus a need for further post-intervention appraisal (Bellmore et al. 2016). In the UK, the NGO sector has been involved both in lobbying for improved river protection, but also in demonstrating practical steps in river conservation. One example is the concept of 'Keeping Rivers Cool' by restoring riparian woodlands. In the wake of climate change, the thermal benefits of improved riparian shading under summer conditions are clear, but advantages for native fish conservation, stream energetics and the reduction of sediment loads also appear likely (Lawrence et al. 2014; Wohl et al. 2015; Thomas et al. 2016b).

Potentially the biggest gains for freshwater conservation would arise when different sectors combine efforts. For instance, the new global initiative, the *Alliance for Freshwater Life* (Darwall et al. 2018), seeks to unite freshwater specialists, from individuals to organizations to governments, who engage in freshwater research, data synthesis, conservation, education and outreach as well as policymaking. Indeed, the global significance of freshwater ecosystems means that all stakeholders – ecosystem managers, policymakers, resource users, NGOs and citizens – should collaborate to make informed decisions that affect freshwater ecosystem viability and productivity. When the voices of inland fisheries professionals and citizens are heard in concert, fisheries success stories often ensue, as evidenced by "good news fisheries" from walleye (*Sander vitreus*) in Red Lake, Minnesota, US, to brown trout in Swedish rivers, among many others (Taylor et al. 2016). Moreover, attempts to engage the public through various forms of science communication and education (*e.g.*, citizen science, participation in decision-making) have great potential to alter individual behaviour (*e.g.*, how they vote, how they relate to water) and generate the political will necessary to protect and restore freshwater ecosystems (Cooke et al. 2013).

This short overview of potential actions indicates that there can be hope for the world's freshwater ecosystems and their biota – but only if these examples inspire action at local, national and global scales in the face of overwhelming pressure. A potential roadmap for the future was outlined in the Rome Declaration (Taylor et al. 2016), which consists of 10 steps – ranging from biological and nutritional to social, economic and political – for responsible inland fisheries that, if followed, will address many emerging threats. However, beyond the sustainability of inland capture fisheries, there remains a lack of specific goals to achieve the conservation of freshwater biodiversity at large. For example, the 2015 United Nations (UN) Sustainable Development Goals (SDGs; see https://sustainabledevelopment.un.org/sdgs) include a goal dedicated to 'life below water' (SDG 14) that is concerned exclusively with the oceans, and the constituent targets say nothing about inland waters (Reid et al. 2017). We are in need of numerical targets that forcefully put the case for protecting freshwater ecosystems (*e.g.*, Griggs et al. 2013). Such targets must: (i) treat the causes, not the symptoms, of freshwater biodiversity degradation; (ii) delineate how they are to be delivered, limiting their openness to interpretation; and (iii) include clear and feasible timelines, with short-, medium- and long-term objectives so they may be periodically reviewed and revised (*e.g.*, 1983 management strategy for Lake Balaton, Hungary) (UNEP 2017). We urge freshwater scientists to engage with the next phases of development of the UN Convention on Biological Diversity, and in particular the post-2020 follow-up to the Aichi Targets, to ensure that these most critically endangered ecosystems are given due prominence. On those actions, the future integrity of fresh waters and their denizens may well depend.

2.6 Conclusions

(1) In the twelve years since the major pressures responsible for global freshwater biodiversity loss were reviewed in (Dudgeon et al. 2006), the prognosis for freshwater biodiversity has worsened, with freshwater species exhibiting steeper declines (declining by 83% between 1970–2014) than their marine or land-based counterparts.

(2) Freshwater biodiversity continues to be underrepresented in the conservation literature (Strayer & Dudgeon 2010) despite estimates that fresh waters are hotspots of endangerment due to the convergence of disproportionately high biological richness and multiple anthropogenic pressures. Habitat degradation, overexploitation and invasive species – stressors all identified by (Dudgeon et al. 2006) – continue to be persistent and ubiquitous threats to freshwater biodiversity with potentially harmful socio-economic effects on human welfare and wellbeing.

(3) Twelve emerging threats to freshwater biodiversity, that are either entirely new since 2006 or have since evolved and require renewed considerations, have been identified herein: (1) changing climates; (2) e-commerce and invasions; (3) infectious diseases; (4) harmful algal blooms; (5) expanding hydropower; (6) emerging contaminants; (7) engineered nanomaterials; (8) microplastic pollution; (9) light and noise; (10) freshwater salinisation; (11) declining calcium; and (12) cumulative stressors. The

Anthropocene has ushered in innumerable direct and indirect anthropogenic effects on diverse freshwater taxa, including amphibians, fishes, invertebrates, microbes, plants, turtles and waterbirds, and there exists strong potential for ecosystem-level changes through bottom-up and top-down responses.

(4) As topographically low and hydrologically connected ecosystems, freshwater lakes, reservoirs, rivers, streams and wetlands incur particular risk because chemical, physical, climatic and biological stressor effects can propagate and accumulate from the atmospheric, terrestrial and riparian environments in which fresh waters are embedded. Multiple stressor problems are therefore a growth area for research. Projected future trajectories of human population growth, accelerating urbanization, increasing irrigation, rising global temperatures and climatic unpredictability are likely to exacerbate human demands for fresh water while also impairing water quality to further compromise ecosystems and threaten biodiversity. There are clear signs that climate change has already directly impacted freshwater ecosystems and ecological processes, and ambitious water infrastructure projects, coupled with the uncertainties generated by climate change, will further alter fresh waters, posing challenges for human water and food security.

(5) To cope with the increasing pressures on water quantity and quality, decision-makers are primarily considering engineering solutions such as the implementation of environmental flows, as well the construction of fishways and the removal of dams. These solutions have been met with relative success but are highly context dependent and require cautionary and targeted research approaches. Conversely, alien introductions, aquaculture and the managed relocation of species are techniques

unlikely to support human wellbeing while maintaining healthy freshwater ecosystems due to the multiple implicit ecological risks.

(6) A desirable alternative is the effective protection of freshwater capture fisheries and the habitats that sustain them. This provides locally sourced, low-cost and nutritious protein in often impoverished areas while also promoting ecological integrity. Freshwater fisheries' contribution to human food security must be reliably assessed, valued and communicated if it is to be included in resource management decisions. At the same time, aquaculture is the fastest growing sector of the food production industry, with potentially major consequences for freshwater biodiversity.

(7) Environmental DNA as a biomonitoring and bioassessment tool could augment biodiversity data acquisition in the future. It offers a promising potential remedy to the insufficient surveillance technologies and baseline data deficiencies presented as common obstacles to emerging threat mitigation efforts. Owing to the fact that fresh waters are subject to multiple pressures, however, any conservation tool or mitigation strategy that mitigates individual stressors will only be effective if co-occurring stressors are also alleviated.

(8) Positive conservation action has brought real and sustained benefits across scales, from local to global, *via* a variety of mechanisms including: regulatory instruments (*e.g.*, The Water Framework Directive); fiscal incentives (*e.g.*, agri-environment schemes); market opportunities (*e.g.*, investments in ecosystem services with financial returns); and/or societal actions (*e.g.*, dam removal, participation in restoration activities, considering freshwater ecosystems when voting in elections).

(9) We are merely at the beginning of the "great acceleration" of the Anthropocene. Indeed, we may even not be able to imagine which environmental challenges we will face in the coming decades. In order to protect biodiversity and to support human well-being, we need to manage fresh waters collectively across sectors and as hybrid systems – managing freshwater ecosystems as both a pivotal resource for humans as well as highly valuable ecosystems.

(10) A global effort, such as that outlined by the *Alliance for Freshwater Life*, the ten steps for responsible inland fisheries in the Rome Declaration and the post-2020 follow-up to the Aichi Targets, is needed to address and reverse global trends in the degradation of freshwater ecosystems, which is to the detriment of both humans and nature. However, how the gap is closed between these lofty goals and the current state of freshwater ecosystems and human use of their services presents an immense but necessary challenge.

2.7 Figures

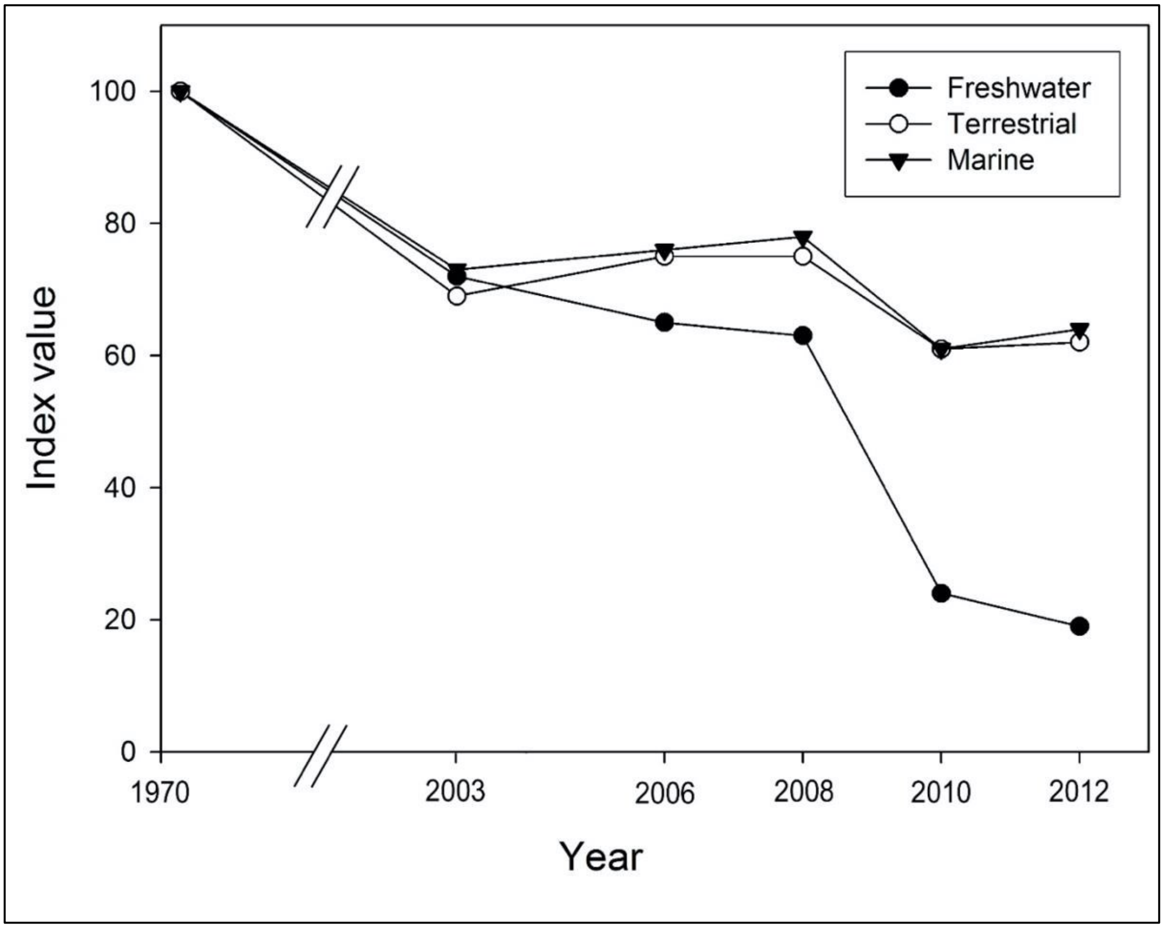


Figure 2-1 The 2016 World Wildlife Fund (WWF) Living Planet Index (LPI) shows population trend data for a collective 'basket' of vertebrates in the freshwater (black circles), terrestrial (white circles) and marine (black triangles) realms, revealing remarkable index decreases among freshwater species. These index declines are relative to a benchmark value of 100 in 1970. Dates given here refer to years in which estimates of abundance were made, as LPI reports typically refer to data from four years earlier (*e.g.*, the 2016 LPI is based on 2012 data). The 2012 index value of 19 for freshwater populations has confidence limits ranging from 11 to 32; the value of 62 for terrestrial populations has limits from 49 to 79; and the value of 64 for marine populations has limits from 52 to 80 (WWF 2016).

2.8 Tables

Table 2-1 Characteristics of emerging threats to freshwater biodiversity: their geographical extent (and focal regions); the severity of their effects; examples of attendant ecological changes; our degree of understanding; and potential options for mitigating threat effects.
For threat severity, categories are severe (red), moderate (yellow) or unclear (grey) and are based on links to freshwater species extinctions demonstrated in the literature. Degrees of understanding include poor (red), fair (yellow) or good (green) and are based on identified knowledge gaps and existing research challenges or unknowns. Relevant references are presented in the corresponding threat sections.

Emerging Threat	Geographic extent	Severity of effects	Ecological changes	Degree of understanding	Mitigation options
(1) Changing Climates	Global	Already causing extinctions; likely to cause more.	Alters species size, range, phenology and survival.	Moderately well understood but high unpredictability.	Global commitments; expand protected areas; restore thermal refugia.
(2) E-commerce & Invasions	Global *(primarily developed markets)*	Significant role in trade of non-native plants and animals.	Creates novel modes of long-distance dispersal.	Largely unregulated activities that are poorly understood.	Online consumer accountability tools; awareness campaigns.
(3) Infectious Diseases	Global *(especially tropical systems)*	Already causing extinctions; likely to cause more.	Alters species survival, with clear ecosystem effects.	Increasingly well understood but high unpredictability.	Improve surveillance; management to favour ecosystem controls.
(4) Harmful Algal Blooms	Global *(warm, nutrient-rich areas)*	Linked to species losses; likely to cause more.	Reduces species growth, survival and reproduction.	Increasingly well understood, some unpredictability.	Improve surveillance; management to favour ecosystem controls.
(5) Expanding Hydropower	Global *(primarily emerging markets)*	Already causing extinctions; likely to cause more.	Fragments river systems, inhibiting species movement.	Well understood, but interactive stressor effects unclear.	Ameliorate passage infrastructure; assess all project impacts.
(6) Emerging Contaminants	Global *(primarily developed markets)*	Unclear how biodiversity will be changed.	Alters some species health, abundance and reproduction.	Largely understudied and thus poorly understood.	Improve medication disposal; advance wastewater treatment.
(7) Engineered Nanomaterials	Global *(primarily developed markets)*	Unclear how biodiversity will be changed.	Causes minimal acute toxicity in some species.	Considerable uncertainty around long-term effects.	Improve detection and characterization; create targeted formulations.
(8) Microplastic Pollution	Global *(primarily developed markets)*	Unclear how biodiversity will be changed.	Potentially detrimental effects on species health.	Considerable uncertainty around long-term effects.	Reduce plastic usage; enact legislation to curb use of specific products.
(9) Light & Noise	Global *(primarily developed markets)*	Linked to species disturbance; likely to continue.	Alters behaviour and physiology of some species.	Well understood, but ecosystem-level effects unclear.	Identify less harmful types; reduce usage; educate users.

Table 2-1 Continued

	(10) Freshwater Salinisation	Coastal lowlands	Linked to species losses; likely to cause more.	Reduces species growth, survival and reproduction.	Increasingly well studied and understood.	Control point sources; strategic release of freshening flow.
20 Ca 40.08	(11) Declining Calcium	Softwater lakes	Linked to species declines; likely affecting foodwebs.	Causes shifts in lake invertebrate assemblages.	Increasingly well understood, but solutions unevaluated.	Further reduce acidic precipitation; replenish calcium in watersheds.
	(12) Cumulative Stressors	Global	Contributing to extinctions; likely to cause more.	Can magnify impacts and create ecological surprises.	Poorly understood with high levels of unpredictability.	Identify multi-purpose solutions that protect biodiversity hotspots.

Chapter 3: "Two-Eyed Seeing": An Indigenous framework to transform fisheries research and management

3.1 Abstract

Increasingly, fisheries researchers and managers seek or are compelled to "bridge" Indigenous knowledge systems with Western scientific approaches to understanding and governing fisheries. Here, we move beyond the all-too-common narrative about integrating or incorporating (too often used as euphemisms for assimilating) other knowledge systems into Western science, instead building an ethic of knowledge coexistence and complementarity in knowledge generation using Two-Eyed Seeing as a guiding framework. Two-Eyed Seeing (*Etuaptmumk* in Mi'kmaw) embraces "learning to see from one eye with the strengths of Indigenous knowledges and ways of knowing, and from the other eye with the strengths of mainstream knowledges and ways of knowing, and to use both these eyes together, for the benefit of all", as envisaged by Elder Dr. Albert Marshall. In this paper, we examine the notion of knowledge dichotomies as well as imperatives for knowledge coexistence and draw parallels between Two-Eyed Seeing and other analogous Indigenous frameworks from around the world. It is set apart from other Indigenous frameworks in its explicit action imperative – central to Two-Eyed Seeing is the notion that knowledge transforms the holder, and that the holder bears a responsibility to act on that knowledge. We explore its operationalization through three Canadian aquatic and fisheries case studies that co-develop questions, document and mobilize knowledge, and co-produce insights and decisions. We argue that Two-Eyed Seeing provides a pathway to a plural

coexistence, where time-tested Indigenous knowledge systems can be paired with, not subsumed by, Western scientific insights for an equitable and sustainable future.

3.2 Preface

It is with *t'ooyak̲s* (Nisga'a for 'thanks') to senior author and Mi'kmaw Elder Dr. Albert Marshall that we (the author team) have come to learn and embrace the concept of *Etuaptmumk* (Mi'kmaw for 'Two-Eyed Seeing') and it is through his guidance that we have envisioned a new path for fisheries research and management. Albert is adamant that the knowledge he has imparted through his work over the decades is not his own to claim, for he is but a conduit for the knowledge of generations. It is thus to those generations of Mi'kmaq Knowledge Keepers, past, present, and future, Albert included, that we express *t'ooyak̲s*.

Andrea Reid is a Nisga'a fisheries scientist who led this effort from Algonquin Anishinaabeg traditional territory. Andrea carries a responsibility to hold place for Indigenous voices in the academe, especially within the natural sciences, where often no space is held, and she is supported and upheld in this work by settler scholar colleagues, allies, and mentors Lauren Eckert, Dr. Nathan Young, John-Francis Lane, Dr. Scott Hinch, Dr. Chris Darimont, Dr. Steven Cooke, and Dr. Natalie Ban. Together, the author team welcomes the reader to this space created expressly for Indigenous and mainstream fisheries knowledges and ways of knowing to come together, to coexist for the "benefit of all" (Marshall et al. 2015) – fish, people, and place – today and in the future

3.3 Introduction

All research, scientific or otherwise, is shaped by philosophical foundations and assumptions. Research paradigms or worldviews are defined and distinguished according to their ontologies (the nature of reality), epistemologies (the theory of knowledge and its validity), axiologies (the nature of values), and methodologies (the purpose and process of research; Wilson 2008; Godfrey-Smith 2009). Collectively, these core philosophical underpinnings reflect researchers' perspectives or views of reality, determine what they count as knowledge and accept as ways of knowing, as well as guide their priorities, choices, and actions in research (Held 2019). It follows that multiple research paradigms exist as there is a plurality of ways in which the world around us is read or interpreted (Guba & Lincoln 1994). However, it is their long-term coexistence that comes into question as colonial forces and linked power imbalances promote certain knowledge types and ways of generating knowledge (*e.g.*, Western science) over others (*e.g.*, Indigenous; Cajete 2000).

The science and management of conventional fisheries is based on a Western or Eurocentric paradigm. It was originally developed in the service of single-stock, large-scale, and commodity-oriented fisheries in north temperate parts of the world (this is evident in early texts such as Beverton & Holt 1957; Royce 1975; Lackey & Nielsen 1980; King 1995). In stark contrast to most small-scale, subsistence-oriented fisheries worldwide, the former relies on a positivistic epistemology (*i.e.*, that there is one "knowable" truth; Berkes 2001; Denny & Fanning 2016) and adheres to an "illusion of certainty" in which nature is predictable and controllable (Charles 2001). The dominant worldview has been both hierarchical and paternalistic (Davis & Jentoft 2001), ascribing to "command and control" resource management (Holling & Meffe 1996). The net result is a global system that is largely failing both ecologically and socially (Pauly et al. 2002; Loring 2013; Brashares et al. 2014), although some managed stocks are rebuilding (Hilborn & Ovando 2014; Krueger et al. 2019; Hilborn et al. 2020). There have been clarion calls for "reinventing fisheries management" (Stephenson & Lane 1995; Pitcher et al. 1998) and a push for fisheries science to adopt an ecosystem-based approach (Holling, 2001; Jackson et al., 2001). However, these have yet to surmount the substantial inertia of current practices and prevailing paradigms (Caddy & Cochrane 2001; Tudela & Short 2005).

Fisheries are tightly coupled and highly complex social-ecological systems – complicating both their management and their study (van Poorten et al. 2011). In a fishery, "resource units" (*e.g.*, fish), "users" (*e.g.*, large- and small-scale fishers), and "governance structures" (*e.g.*, rules, governing bodies) exist and are separable, but all interact to produce outcomes on a system level (Ostrom 2009). They are considered 'complex' in that they involve two-way feedbacks and are characterized by nonlinearity, uncertainty, multiple scales, self-organization, and adaptation (Berkes, 2003). Given these features, there is no single comprehensive or "correct" perspective in a complex fisheries system, but it is perhaps best understood through a plurality of ways (Olsson et al. 2004). Particularly at this time of stagnating or declining fisheries catches (Watson et al. 2013), intensifying fishing effort and poor management (Pitcher & Cheung, 2013), as well as a lack of complete data for many of the world's fisheries (Costello et al. 2012), there is an urgency to improving this understanding and our actions towards complex fisheries problems, as well as significant potential costs (*i.e.,* ecological, economic, socio-political etc.; *e.g.*, Pomeroy et al., 2007) in not doing so.

Not only would it behoove fisheries scientists to use all and the best tools and knowledge available at this time of crisis, irrespective of their origin and the perceived objectivity and superiority of Western scientific approaches (TallBear 2014a), but this would importantly serve decolonial and reconciliatory efforts that help rectify uneven power relations, knowledge inequalities, and other racially-linked and unjust dynamics in fisheries (Latulippe 2015; Held 2019).

Addressing this complexity and confronting existing problems, *Etuaptmumk* (Mi'kmaw for 'Two-Eyed Seeing') provides a conceptual framework for equitably embracing multiple perspectives within a system. Mi'kmaw Elder Albert Marshall defines Two-Eyed Seeing as "learning to see from one eye with the strengths of Indigenous knowledges and ways of knowing, and from the other eye with the strengths of mainstream knowledges and ways of knowing, and to use both these eyes together, for the benefit of all" (Bartlett et al. 2012). Two-Eyed Seeing has been used to promote the coexistence of disparate paradigms across a variety of fields – for instance, in education (Hatcher et al. 2009; McKeon 2012), medicine (Martin 2012; Hall et al. 2015), and wildlife health (Kutz & Tomaselli 2019) – and while a growing number of studies point to its promise for fisheries research and management (*e.g.*, Giles et al. 2016; Mantyka-Pringle et al. 2017; Abu et al. 2019), there has yet to be equivalent comprehensive consideration of Two-Eyed Seeing applications in this domain.

Here, we move beyond the all-too-common dialogue of integrating, combining, or incorporating (commonly used as euphemisms for assimilating) other knowledges and ways of knowing *into* Western science, and instead build an ethic of knowledge coexistence and complementarity in knowledge generation using Two-Eyed Seeing as a guiding framework. We first examine the notion of knowledge dichotomies and imperatives for knowledge coexistence (**Section 3.4**) and then draw parallels between Two-Eyed Seeing and other analogous Indigenous frameworks (**Section 3.5**). Next, we examine aquatic and fisheries case studies that embrace Two-Eyed Seeing as they co-develop questions, document and mobilize knowledge, and co-produce insights and decisions (**Section 3.6**). Lastly, guided by these works, we detail ontological, epistemological, axiological, and methodological changes required to transform fisheries research and management for an equitable and sustainable future (**Section 3.7**).

3.4 Beyond Dichotomous Discourse

Defining Indigenous knowledge is shifting away from a focus of 'utility' (what it can do for Western science) and reductionism (how it provides "data" to Western scientific analyses). However, delineating what Indigenous knowledge is and how it operates has remained largely the purview of external organizations, governments, institutions, and researchers rather than by Indigenous peoples them/ourselves (McGregor 2004a; Battiste & Henderson 2000; Eckert et al. 2020). The associated terminology has been evolving – away from 'tradition' or 'folk' terms (*e.g.*, traditional ecological knowledge or TEK) that once dominated the conservation literature (Gómez-Baggethun et al. 2013) – towards language that connotes the contemporary and diverse realities of these knowledge systems (Battiste, 2005). Indigenous knowledge (our term of choice – but see Cruikshank, 1998 for an alternate view) is now widely accepted as "a cumulative body of knowledge, practice and belief evolving by adaptive processes and handed down through generations by cultural transmission, about the relationship of living beings (including humans) with one another and with their environment" (Berkes, 2018). A critical addition to this definition (see glossary in **Table 3-1**) is that this 'situated knowledge' is neither separable from the knowledge holders or keepers, nor is it divisible from the environment in which it is embedded (McGregor 2004a). We define this term here for the purpose of the present dialogue while also recognizing problematic aspects of doing so given that Indigenous knowledge is not uniform across all Indigenous peoples (hence, why this term is often referred to in the plural form: Indigenous knowledges). For many it is not a definable object, but instead a way of being and living in the world (Battiste & Henderson 2000).

Society under colonial influence has long perceived Indigenous knowledge as 'the other' and in binary opposition to Western scientific knowledge (Battiste 2005). Where the latter is thought to be quantitative, factual, analytical, reductionist, and literate, the former is assumed qualitative, anecdotal, intuitive, holistic, and oral (Nadasdy 1999; Mistry & Berardi 2016; Berkes 2018). According to Castleden and colleagues (2017), who argue that "we need to challenge the dichotomy discourse," this dualistic and simplified view leads directly to notions of knowledge inequality and an othering process that favours continued division over coexistence. There are certainly distinctions in attributes that lead to both having individual strengths in specific contexts, but there is no righteous hierarchy of knowledge systems where one is systematically better or consistently outperforms another (Berkes, 2018). Both center on improving our understanding of the world around us (Cajete 2000) – an end that surely becomes more achievable through a plural coexistence (**Table 3-1**) (Howitt & Suchet-Pearson 2006) where time-tested Indigenous knowledge systems can be paired with revelatory Western scientific insights (Pierotti & Wildcat 2000; Benessia et al. 2012; Mistry & Berardi 2016).

The prevailing solution to confronting this plurality has been 'knowledge-integration' (Nadasdy 1999), a process fraught with risks and limitations. The process aims to bridge multiple knowledges, bringing new information into an existing body of knowledge (generally that which wields greater power; Hart 2010), as well as to identify key similarities and differences so the latter can be minimized, and knowledge consolidation simplified (Bohensky & Maru 2011). But, as noted above, Indigenous knowledges and ways of knowing are far more than simply "information" to be subsumed into the mainstream of Western science (Agrawal 1995) – which in essence serves only to strengthen Western science for its own ends and "to concentrate power in administrative centers, rather than in [Indigenous] communities" (Nadasdy 1999). For these reasons, some scholars have abandoned potentially problematic terms such as integration or bridging, while others advocate that we can "update their meaning and use" as Berkes (2003) has done with respect to "resource" and "management" — both options are viable ones so long as there is concomitant recognition that language choices reflect biases, and can even perpetuate colonial inequalities, so users of these terms (or their alternatives) must be explicit and transparent about their intentions with their usage. Here, we use terms such as "pairing," or better yet "adopting a Two-Eyed Seeing approach", to speak to circumstances where Indigenous and Western scientific knowledge systems contribute in parallel to produce an enriched picture and mutual understanding – while recognizing that ultimately it is the actions taken that matter most, rather that the words used to describe them.

Pressure is mounting across spheres (*i.e.,* legal, practical; **Table 3-2**) and scales (institutional to global) to pair Indigenous knowledge systems together with Western scientific practices (Ogar et al. 2020). Regardless of terminological preferences, what we sorely need are approaches that: remedy, rather than reinforce, existing power relations; respect differences, instead of suppress them; and uphold, as opposed to diminish, their unique strengths (Muller 2012). These latter elements comprise yet another imperative, a moral one (Paton 1971), to conduct research in a way that promotes social justice and self-determination (Ludwig 2016; Held 2019; Artelle et al. 2019). In sum, a plural coexistence holds multiple possibilities within it: (i) improving our understanding of complex systems, with insights and information from multiple knowledges contributing to an enriched picture; (ii) conforming to legal norms and practical requirements, without which many research programs simply would not be advanced by today's funding bodies and research ethics boards; and (iii) answering to undeniable moral queries about what is 'right' in terms of human rights and equality.

3.5 Models of Knowledge Coexistence

While as diverse as the ecosystems to which they are inextricably linked, Indigenous worldviews globally share a number of philosophical and spiritual underpinnings (Simpson 2000). The knowledge held may be highly distinct across groups, but the process through which knowledge is generated predominantly ascribes to a paradigm that is cyclic, interconnected, and fundamentally relational (McGregor 2004a) – where knowledge itself depends on relationships and connections between living beings (including humans) and non-living entities (as above; Wilson 2008). They tend to embrace both "communitism" (the search for and commitment to Indigenous community and values; Weaver, 1997) as well as respectful individualism and cultural sovereignty (where individual and cultural differences are upheld and maintained rather than homogenized;

Gross 2003). Indigenous worldviews thus have potentially profound implications for how knowledges can come to be complementary and coexist, rather than compete or be subject to assimilation.

In their formative writing on multiple evidence base (MEB) approaches, Tengö and colleagues (2014) identify a need for new tools and approaches for co-developing questions, documenting and mobilizing knowledge, and co-producing insights and decisions – all under the guiding principle of valuing diversity in knowledge systems. In their view, "a MEB approach emphasizes the complementarity of knowledge systems and the values of letting each knowledge system speak for itself, within its own context, without assigning one dominant knowledge system with the role of external validator" (Tengö et al. 2014). A key point emerges: each way of knowing should not be assessed by external referents, but rather by internal criteria (Klenk & Meehan 2015). MEB approaches seek to connect distinct knowledge systems (Alexander et al. 2019), often through parallel lines of Indigenous and Western scientific inquiry (Tengö et al. 2014), but mechanisms and successful examples of this or equivalent approaches in practice, especially in an aquatic or fisheries context, have been few and far between (*e.g.*, Mackinson 2001; Laidler 2006; Cooke et al. 2020).

A number of long-standing and/or contemporary Indigenous frameworks, although scarcely represented in the academic literature (and where they are, it is largely at the hand of Indigenous scholars and/or in Indigenous-focused journals), may answer directly to this need. They offer means to conceptualize and operationalize the cross-fertilization and coming together of distinct knowledge systems – epistemic pluralism (Carter 2017) through an Indigenous lens. Conceptual frameworks are reflective of the knowledge one privileges (Kovach 2010) and their visualization can guide important research choices (Latulippe 2015). The subsequent four highly visual and conceptual frameworks (**Figure 3-1**; **Table 3-1**) exemplify that highly comparable approaches can arise across distinct and distant Indigenous cultures and suggest that these are likely but a small selection of a much larger number of Indigenous conceptualizations for promoting knowledge coexistence. The following descriptions provide references to key sources – many of which are written by members of the cultures from which they stem (and to which the author team does not belong, with the exception of Elder Dr. Albert Marshall of the Mi'kmaq Nation discussed in **Section 3.6.3**).

(i) The *Kaswentha* (Haudenosaunee for 'Two Row Wampum'; **Figure 3-1A**) is a 17th century treaty belt to record an agreement between the Haudenosaunee Confederacy and Dutch settlers in eastern New York (Ransom & Ettenger 2001). It contains two rows of purple beads that each represent the different vessels of the Dutch (ships) and the Haudenosaunee (canoes). They are surrounded by white beads that symbolize the shared "river" of existence (McGregor 2002). These distinct vessels remain separate, each containing their own laws, traditions, and rights and neither disrupting the integrity or process of the other, though they travel together and work in partnership on common problems (Rathwell et al. 2015). Though a historical model of coexistence, it remains salient today where it is being applied to environmental protection and restoration programs (Ransom & Ettenger 2001), water quality monitoring projects (McGregor 2002), and resource co-management initiatives (Stevenson 2006).

(ii) On the north-eastern coast of Arnhemland, Australia, the Yolngu people have a long-standing framework that centers around *Ganma* (a particular confluence of sea water and fresh water; Christie 2007). The two waters (**Figure 3-1B**) represent distinct knowledge systems that come together, interact, but maintain their separateness akin to isohalines in a lagoon or estuary (Muller 2012). Rather than compromising one another and becoming a homogenous whole, this 'Two Ways' or 'Both Ways' metaphor centers around the creation of a new space where two understandings and knowledges can come together equitably and work in parallel – ultimately creating greater shared understanding (Bat et al. 2014). It is used as a mechanism to this day to ensure that Yolngu are represented equally in the thinking and planning of both land and sea management (Marika 1999; Dhimurru Aboriginal Corporation 2013).

(iii) In *Aotearoa*/New Zealand, the *Waka-Taurua* (Māori for 'Double-Canoe'; **Figure 3-1C**) is a contemporary metaphorical framework where two canoes (each representing distinct knowledge systems) are lashed together temporarily for a common purpose (*e.g.*, operating a large seine; Maxwell et al. 2019). It recognizes inherent differences on both sides and is based on the assertion that respective knowledges, values, and actions are not made to fit into each other. As above, there is "negotiated space" (in this case, between canoes) where knowledge systems can interface and innovate (Mila-Schaaf & Hudson 2009; Smith 2012). It is embedded within *Kaitiakitanga* (a Māori concept for reciprocal care between people and place; Roberts et al. 1995) and has been applied to uphold Māori and Western scientific knowledges within marine co-management and co-governance (Maxwell et al. 2019).

(iv) *Etuaptmumk* or Two-Eyed Seeing (**Figure 3-1D**), as previously introduced, draws together the strengths of mainstream and Indigenous (specifically Mi'kmaw) knowledges (Bartlett et al. 2012). This binocular framework leads to a "wider, deeper, and more generative field of view" than could be achieved by either perspective or knowledge system in isolation (Iwama et al. 2009). It shares with the above frameworks the notion of working collaboratively across knowledge systems on a common problem (Berkes, 2018), and as with the Double-Canoe it centers on a cultural conservation concept, that of *Netukulimk* where ecological integrity is maintained for the next seven generations (Prosper, McMillan, Davis, & Moffitt, 2011). It too creates space for common ground and respects differences by reducing us/them dichotomies and breaking down the compartmentalization of knowledge that leads to domination and exclusion (McMillan & Prosper 2016).

While Two-Eyed Seeing bears substantial resemblance to the other presented frameworks, it is perhaps set apart in its explicit action imperative. Central to Two-Eyed Seeing is the notion that knowledge transforms the holder, and that the holder bears a responsibility to *act* on that knowledge (Hatcher et al. 2009). *Netukulimk* implores one to uphold their responsibilities to future generations (Prosper et al., 2011); much like the early conceptual space of conservation biology (Soulé, 1985) but with emphasis here on responsibility to the place from which the knowledge emerges. To do so, *Netukulimk* uses the two perspectives made available through Two-Eyed Seeing processes to improve those very actions (McMillan & Prosper 2016). This is not to say that the other frameworks do not share similar motivations or implications (recalling *Kaitiakitanga*), but rather that Two-Eyed Seeing uniquely moves beyond 'unified-knowledges' as the end goal, to 'unified-knowledges-and-here-is-what-we-are-compelled-to-do' as the ultimate realization of the framework. It is perhaps in part due to this assertion that Two-Eyed Seeing has extended past conceptual spaces, and that there are a growing number of concrete examples of Two-Eyed Seeing in practice. The big question is not *whether* Two-Eyed Seeing (or like frameworks) will help us confront challenges in a post-colonial society or amidst environmental crises, but, in the words of Lawless and colleagues (2013) it is "rather, *how* they might be configured and applied." A significant challenge to date is the lack of pre-existing guidelines as the application of these frameworks depends highly on the specific context and the receptiveness of all actors involved (Denny & Fanning 2016).

3.6 Two-Eyed Seeing in Practice

To gain insight into how Two-Eyed Seeing approaches can and have been applied in aquatic and fisheries research and management contexts, we examine three recent case studies that speak directly to the abovementioned need for tools and approaches for: (*a*) co-developing questions; (*b*) documenting and mobilizing knowledge; and (*c*) co-producing insights and decisions (Tengö et al. 2014). Given its place of origin (Eastern Canada; Bartlett et al. 2012), these examples of Two-Eyed Seeing in practice are all Canadian-based, but we draw parallels where possible to other pertinent studies centered in other parts of the world. The subsequent case studies each take a holistic approach, considering more than strictly fish- or fisheries-related parameters to include multiple indicators of aquatic ecosystem health (**Sections 3.6.1 & 3.6.2**) and broader societal implications for fisheries co-management and co-governance (**Section 3.6.3**).

3.6.1 Co-developing Questions in the Slave River Delta

This first case study centres on the theme of developing power-neutrality in the research process. In response to a co-developed set of questions, the collaborative author team of Mantyka-Pringle et al. (2017; comprising Indigenous community members, academics, and other groups) employed a participatory modelling approach (Bayesian Belief Networks; BBNs) as the central methodology for operationalizing Two-Eyed Seeing.

In the Slave River Delta in the Northwest Territories of Canada (**Figure 3-2A**), significant resource development activity upstream (*e.g.*, oil sands operations in northern Alberta, the W.A.C. Bennett Dam in northern British Columbia) is having profound impacts on ecosystem health and societal well-being downstream (Dagg 2016). This is a place where hunting and fishing comprise a vital part of Indigenous life – for example, in one Slave River community (Fort Resolution), 66% of all Indigenous peoples participated in hunting and fishing in 2013, and 92% of all households ate meat or fish derived from those activities that year (NWTBS 2014). In direct response to growing community concerns about the health of fish specifically, a diversity of 'actors' in the region (three First Nations, three Métis organizations, two towns, a college and research institute, and various territorial and federal government agencies) united to create the Slave River and Delta Partnership (SRDP) in 2010. Their main goal was to develop community-based monitoring activities throughout the region, for which they solicited the help of multiple academic partners (six universities; Dagg 2016). At an aquatic ecosystem health workshop in 2011, the SRDP and various academics co-developed three key central questions ("i. *Is* *the water safe to drink?* ii. *Are the fish and wildlife safe to eat?* and iii. *Is the ecosystem healthy?*") to which Mantyka-Pringle et al. (2017) offered responses.

At the 2011 workshop, >100 participants identified key indicators of aquatic ecosystem health along two distinct and complementary lines of inquiry: Western science and Indigenous knowledge. Where water quality and fish health could be described, respectively, in terms of 'turbidity' (in Nephelometric Turbidity Units) or 'fish external anomalies' (number of cysts, tumors, lesions and malformations) through a Western scientific lens, they could likewise be understood in terms of 'the physical appearance of water' (changes in water visibility or movement over time) or 'fish aesthetics' (changes in frequency of lesions or deformities over time) through an Indigenous lens. Data to inform Western science indicators (n=19) were obtained through field observations and document reviews between 2011 and 2015, while key informant interviews with Elders in 2014 (Bradford & Bharadwaj 2015) formed the basis for Indigenous knowledge indicators (n=22). Two-Eyed Seeing was the core principle that informed how these two knowledge systems (and 41 indicators) would co-exist, and BBNs served as the central methodology for operationalizing Two-Eyed Seeing. In 2015, the team led an expert elicitation process where they combined visual, narrative, and textual tools to have key knowledge holders (an equal number of Elders, harvesters/fishers, government staff, and scientists) assess the causal links between the indicators and the three guiding questions above. Experts evaluated: the importance of indicators and their interactions; the state of indicators compared with the past (low, medium, or high); their own level of expertise for each assessment (to populate the BBN with uncertainty estimates); and the resulting model output and behaviour (Mantyka-Pringle et al. 2017).

By bringing together interview transcripts, field data, existing models, and expert judgement via participatory modelling, this team was able to provide a power-neutral approach to answering a co-developed set of questions and produce a co-authored report (*i.e.*, Mantyka-Pringle et al. 2017 with the SRDP listed as senior author). Together, they determined a low probability that the social-ecological system is as healthy as it once was, and, they found that where multiple Western science indicators were graded as 'moderate' compared with the past, Indigenous knowledge indicators were graded as 'low' – suggesting either that Western science is less able to detect incremental change given shorter timescales, or an unsubstantiated perception of change by Indigenous knowledge holders, or both (Moller et al. 2004). Notably, as BBNs can readily be updated as new knowledge becomes available, this study serves as an initial model that can be refined over time. Mantyka-Pringle et al. (2017) adds to the growing narrative that BBNs provide an effective means to widen the evidence base (*e.g.*, Johnson et al. 2013; Ban et al. 2014), allowing for both quantitative and qualitative information to come together for a more holistic understanding of a complex system and enabling knowledge-inclusive partnerships to exist and be effective.

3.6.2 Documenting and Mobilizing Knowledge in the Saskatchewan River Delta

This second case study, Abu et al. (2019), centres on the theme of consilience – the congruence or agreement between the approaches to a topic or question by different knowledge or information systems. Here, Indigenous knowledge, archival records, and information collected using modern scientific instruments are brought together using the

Two-Eyed Seeing framework, and their consilience is examined for a vast array of hydrology, fish and wildlife, and vegetation indicators of ecosystem change.

The Saskatchewan River Delta – North America's largest freshwater delta (**Figure 3-2B**; 10,000 km^2) – shares a similar context with the example above, where upstream anthropogenic activities (primarily the E.B. Campbell, Gardiner, and Nipawin Dams) have profoundly reshaped system hydrology as well as fish and wildlife populations, provoking both community concern and the 2012 formation of a collaborative community-academic partnership in response (Patrick 2014). One of the main goals of the partnership centers on finding ways for Indigenous communities and academic researchers to work together as equals, where both Indigenous knowledge and Western science are equally valued and unified to improve collective understanding of ecosystem change in the delta. Academic partners from the University of Saskatchewan identified three main questions that they explore in Abu et al. (2019): "i. *How can we learn about long-term social-ecological change from diverse knowledge holders?* ii. *How can we provide for the coexistence of plural forms of knowledge while engaging in respectful critique?* and iii. *How can we document the relative contribution each knowledge system provides and explain how each helps to fill in the gaps of the other?*".

Through literature review, the authors outline various approaches for bridging knowledge systems (touching on a number of the concepts described here in **Sections 3.4 & 3.6**) and identify Two-Eyed Seeing as the guiding framework that will enable them to address their first two central questions. The article drew on three sources of evidence of ecosystem change in the delta. The first line of evidence was Indigenous knowledge drawn from key informant interviews with Elders and harvesters (inclusive of fishers, hunters, and trappers) in 2014, which included accounts of key historical events and perceived changes in the system (Abu & Reed 2018). Once transcribed and analyzed, preliminary results were presented back to the community for review and approval. The second evidence base was archival records from the Provincial Archives of Saskatchewan on key historical events and past system changes, as well as information on resource-related policies (*e.g.*, permits, quotas, regulations) and government correspondence (*e.g.*, letters, petitions). The third form of evidence was instrumental observations (*i.e.,* information collected using scientific instruments such as water gauges, or through field records such as fish-landing data). All three evidence bases included both quantitative and qualitative information that were brought together to address their third guiding question using a simple but elegant means of examining knowledge congruence (c.f., Jackson et al. 2014) where knowledge systems were indexed as either consistent (in agreement), inconsistent (in disagreement), or an evidence type was lacking for comparison. This was performed for multiple indicators of change in hydrology (n=12), fish and wildlife (n=16), and vegetation (n=9).

Taking this MEB approach guided by Two-Eyed Seeing, this team documented one evidence base (*i.e.*, Indigenous knowledge; Abu & Reed 2018) and mobilized two others (*i.e.,* archival records and instrumental observations) for a novel and holistic approach to examining the state of a complex social-ecological system. They found a high degree of convergence across knowledge systems, where adverse changes in hydrology (83% congruent indicators), fish and wildlife (94%), as well as vegetation (100%) are reflected across all since the development of upstream dams. Incongruent indicators, as examples, included Indigenous knowledge signaling currently poor water quality (whereas instrumental observations declare it ‘safe’) and a high abundance of northern pike (*Esox lucius*, Esocidae; *wícégãpís* in Cree; whereas instrumental observations find it near zero – but this may be explained by a decline in commercial interest, and thus fish-landing data, for this species). For six out of nine vegetation indicators, pertaining largely to knowledge of berries and other flowering plants, Indigenous knowledge provided the sole source of information available. Given the overall high degree of agreement between knowledge systems (as similarly found in Jackson et al. 2014; Service et al. 2014), Abu et al. (2019) provide further reason to be confident about understanding ecological phenomena through more than a strictly traditional (*i.e.,* Western science) lens.

3.6.3 Towards Co-producing Insights and Decisions on *Unama’ki*

For this third case study, Giles et al. (2016), we move beyond examples of uniting disparate knowledges to an instance of bringing together disparate experiences with respect to gaining insights about a fishery and making decisions based on those contrasting understandings. We also move from Northern and Western parts of Canada to the East Coast where the Two-Eyed Seeing concept came into being in *Mi'kma'ki* – the traditional and contemporary territory of the Mi'kmaq people.

Unama'ki/Cape Breton Island (**Figure 3-2C**) is home to the largest Indigenous community in Atlantic Canada and the largest Mi'kmaw community on the continent: the Eskasoni First Nation (population ~4,000; MacPherson et al. 2016). Located along the Bras d’Or Lakes and surrounded by the Atlantic Ocean, the Eskasoni community is deeply engaged in fishing activities for food, social, and ceremonial (FSC) purposes as well as commercial – with a community-owned and -operated fishing company that employs >150 fishers and contributes to nearly 10% of Eskasoni's annual revenues (Eskasoni Band Council 2014). Since 1999, Eskasoni has been home to the *Unama'ki* Institute of Natural Resources (UINR) – representing Eskasoni and the four other Mi'kmaq communities on the island (*i.e.,* Membertou, Potlotek, Wagmatcook, and We'koqma'q) –and this is a group that, consistent with the previous two case studies, was formed in response to rising community concerns regarding natural resources (especially fisheries) and their sustainability. One of UINR's central goals is to strengthen research and natural resource management while maintaining Mi'kmaq knowledges and worldviews. To this end, they frequently partner with external governments, organizations, and universities on key environmental concerns (UINR 2016). One such partnership, Giles et al. (2016), involved researchers from both Dalhousie University and UINR, as well as commercial fishers and representatives from the Eskasoni First Nation. Together, they examined Indigenous inclusion in policy-level fisheries decision-making in Canada, using Eskasoni's American eel (*Anguilla rostrata*, Anguillidae; *Kataq* in Mi'kmaw) fishery as a model system.

The American eel has been vital to the Mi'kmaq for thousands of years (primarily used now for FSC purposes and largely absent from Eskasoni's commercial fishery; Davis et al. 2004), but it has come under threat in recent decades due to the combined effects of habitat destruction and fragmentation from hydroelectric development, as well as targeted commercial fishery operations and other threats (Cairns et al. 2014). Dramatic declines (65% fewer maturing eels in the Great Lakes and upper St. Lawrence River area between 1996 and 2010) have led the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) to list the American eel as threatened in 2012 and prompted its consideration for listing under Canada's 2003 *Species at Risk* Act (SARA).

While SARA states that “the traditional knowledge of the aboriginal peoples of Canada should be considered in the assessment of which species may be at risk and in developing and implementing recovery measures,” there are inherent challenges that arise from the attempted ‘integration’ of Indigenous knowledges and values into government level policy, which Giles and colleagues (2016) examined. Moreover, FSC fisheries are constitutionally protected in Canada and the listing of a culturally significant species like eel could have profound impacts on community subsistence, well-being, as well as constitutional and treaty rights. It follows that Mi'kmaq inclusion in the COSEWIC and SARA processes for eel should be a given, but Giles et al. (2016) find minimal evidence that Mi'kmaq were included in the process.

In 2014, using Two-Eyed Seeing as a guiding framework (as UINR does through all its activities; UINR 2016), Giles and colleagues (2016) interviewed both Eskasoni eel fishers (about the fishery and linked knowledges) as well as federal government representatives involved in COSEWIC and SARA assessments (about the process and its “use” of knowledge). They found that despite the existence of an Aboriginal Traditional Knowledge Sub-Committee (ATK SC) within COSEWIC, as well as various other measures within SARA (*e.g.*, the National Aboriginal Council on Species at Risk (NACOSAR) and Aboriginal Funding for Species at Risk (AFSAR), which were not even raised by respondents during interviews), “the full understanding of a Mi'kmaq knowledge system is not reflected in [current] management decisions” (Giles et al. 2016). Additionally, Mi'kmaq eel fisheries were found to be underpinned by the values of kinship, relationality, generosity, and *Netukulimk*, whereas the governmental approach to eel fisheries was found to be governed by a Western scientific worldview that instead prioritizes process, compartmentalization, economic benefits, and conservation.

Reconciling the two vastly differing approaches to knowing and managing the eel fishery sustainably presents a considerable challenge. From the perspective of government respondents, the barriers are logistical (citing: no formal process for 'integration'; concerns around data ownership), conceptual (no space in the process for cultural or spiritual components; the two systems operating on incompatible time scales – immediate *vs.* seven generations), and communication-based (using different languages and interpretations; unresolved historical traumas and issues of mistrust between the Mi'kmaq and the Canadian Government). Nevertheless, the authors report "considerable opportunity" for bringing Mi'kmaq knowledge systems to bear on the COSEWIC and SARA processes – highlighting specific mechanisms in their workflow (*e.g.*, ATK SC, NACOSAR, AFSAR) and flagging areas that could be enhanced (*e.g.*, through the inclusion of community advisory boards, scenario-building activities), as well as identifying multiple benefits of doing so *via* a Two-Eyed Seeing approach (*i.e.,* promoting cross-cultural and enriched understandings, fostering mutual respect, and upholding constitutional and treaty rights). Here, we find a critical examination of the involvement of Indigenous peoples and knowledges in policy decision-making and an envisioned path for meaningful and equitable co-governance based on a Two-Eyed Seeing approach – similar arguments and scenarios have been built around the Two Row Wampum model (see Stevenson 2006), the Two Ways philosophy (see Muller, 2014), as well as the Double-Canoe framework (see Maxwell et al. 2019).

Two-Eyed Seeing has had visible traction in co-developing questions, documenting and mobilizing knowledge, and co-producing insights, and it holds promise for guiding policy decision-making in fisheries. But, without clear evidence here of the latter coming to full fruition (*i.e.,* true decision co-production), this calls into question whether the mutual understanding generated through Two-Eyed Seeing is of much consequence if it is not reflected in policy decision-making, which ultimately determines how a fishery is managed, studied, perceived, and utilized. It also raises the issue of whether Indigenous knowledge systems are only being valued here because they are supported by and in strong congruence with Western science – but continued colonial sentiment throughout governing bodies prevents their full and equitable inclusion into policy decision-making.

There needs to be a fundamental rethinking in how we come to know and manage fisheries that allows space for multiple ways of knowing if we are to fulfill our obligations (legal, practical, moral, as discussed in **Section 3.4**) and achieve its co-benefits. As examples, the inclusion of Indigenous knowledge systems in fisheries research and management has been shown to: offer technological shifts that improve fisheries selectivity and sustainability (Menzies & Butler 2007); enhance early warning systems for sea state forecasting (Sethi et al. 2011); reverse declines in the abundance and size of exploited species (Frid et al. 2016); yield otherwise inaccessible ecological insights such as missing baseline information (Marin et al. 2017; Eckert et al. 2018); as well as play a critical role in the improvement as well as the collective adherence to fisheries policy (Johannes et al. 2000; Berkes 2018). However, rarely are the past and present impacts of colonialism on these knowledge systems and their power recognized, let alone rectified, which is both "practically and politically dangerous" (Butler 2006) for all of the reasons presented herein.

3.7 Re-envisioning Fisheries Research and Management

Significant strides have been made over the past decade in decolonizing research and methodologies (Wilson 2008; Smith 2012; Kealiikanakaoleohaililani & Giardina 2016; Held 2019) and in defining Indigenous worldviews *as* research method – as a defensible paradigm to guide scholarly inquiry (Kovach 2010; Latulippe 2015; McGregor et al. 2018). Held (2019) brings together many of these and additional works as she defines an Indigenous research paradigm in terms of its own philosophical assumptions (*i.e.,* ontology, epistemology, axiology, methodology) and in relation to other major paradigms that inform primarily social inquiry (*i.e.,* positivist, postpositivist, constructivist, transformative, and pragmatic research paradigms). From this foundation and informed by philosophical examinations of conventional fisheries alternatives (Berkes, 2001, 2003) as well as the case studies above, we can collate the purposes, main assumptions, and worldviews that underpin Western and Indigenous approaches to fisheries research and management (**Table 3-3**), and identify avenues for ontological, epistemological, axiological, and methodological transformation in fisheries that allow for the full operationalization of Two-Eyed Seeing.

Instead of "fishing-as-business" (Berkes 2003), Indigenous fisheries are often driven by ethics of sustainability (*e.g.*, *Netukulimk*, *Kaitiakitanga*), protecting the present and future well-being of fish, people, and place (Roberts et al. 1995; Prosper et al. 2011; McMillan & Prosper 2016; Maxwell et al. 2019). While modern fisheries scientists acknowledge uncertainty in their models and projections (e.g., credibility envelopes) and contextualize their findings as being based on the best available evidence at the time, subject to change as new data arise, their discipline historically stems from a realist ontology (that there is but one knowable reality), an objectivist and empirical epistemology (where research findings are 'true'), a values-free axiology (where influences and biases are denied), and an experimental and top-down methodology (through which hypotheses are verified and findings universal). Of course, modern fisheries scientists openly acknowledge uncertainty in their models and projections (*e.g.*, credibility envelopes) and contextualize their findings as being based on the best available evidence at the time, subject to change as new data arise. In contrast to the more conventional fisheries notions, Indigenous fisheries ascribe to a relativist ontology (where multiple socially-constructed realities exist), an intersubjective epistemology (that respects multiple ways of knowing and forms of knowledge), a values-centered axiology (where relational accountability is key), and a participatory and contextualized methodology (that is knowledge-inclusive and its findings specific to place; Held 2019). The former is characterized by reductionism, positivism, and 'expert-knows-best' science, while the latter adopts complex systems thinking and is inclusive of local knowledge systems (Berkes, 2003). This culminates, on the one hand, in a Western scientific perspective that is founded upon a utilitarian worldview where humans are in control of nature (as described in 3.3), and an alternate perspective that humans are part of ecosystems – where, in the latter case of Indigenous fisheries, it is human actions rather than natural systems that are subject to governance and structure (Berkes 2001, 2003). The aim here again is not to pit one approach against the other or to place them at irreconcilable odds, but rather to highlight their distinctiveness given that both have individual strengths in specific contexts.

Frameworks such as Two-Eyed Seeing that enable parallel lines of inquiry to come together (**Figure 3-3**) require an openness to other ways of being and knowing on both sides that historically has not been reflected in the mainstream approach to fisheries research and management (Denny & Fanning 2016). As made evident by the case studies above, knowledge coexistence "for the benefit of all" (Marshall et al. 2015) depends on who is at the table and their receptiveness to alternative modes of knowing and generating knowledge. From these case studies, there are clear actionable steps that emerge that can inform other research programs moving forward (**Figure 3-4**). For instance, in Mantyka-Pringle et al. (2017) and Abu et al. (2019), Indigenous knowledge and Western science were clearly placed on equal footing, with both serving as evidence bases to inform various indicators of aquatic ecosystem health. In the case studies presented above, most approaches were highly participatory, being co-developed, co-run, and/or co-evaluated by the collaborative teams conducting the research, with evaluations primarily measured against internal rather than external referents (*e.g.*, experts evaluating their own expertise as well as model output (Mantyka-Pringle et al. 2017); researchers bringing their preliminary interview results back to the community for review and approval (Abu et al. 2019)). All studies were set in motion by communitism – where Indigenous communities identified the original need(s) and invited external partners in accordingly, which was reflected in co-authorship (UINR partners in Giles et al. 2016; and the SRDP as a collective in Mantyka-Pringle et al. 2017) or acknowledgements (Abu et al. 2019). Each study created a unique current or future pathway for Two-Eyed Seeing in their context, and all are poised for operation in the long term. They demonstrate the context-dependent nature of this framework, and that solutions are not one-size-fits-all scenarios – in fact, knowledge unification was achieved through a multiplicity of mechanisms that matched their individual circumstances.

The prevailing paradigm that was conducive to Two-Eyed Seeing in all three case studies shares many parallels with Indigenous fisheries approaches and worldviews (**Table 3-3**). Each study respected multiple realities (reflective of a relativist ontology), considered multiple knowledges as valid and equal (an intersubjective and pluralistic epistemology where experiential and relational knowledge is equally valued), embraced relational accountability by promoting respectful representation and reciprocity (a value-centered axiology), and carried out highly inclusive and situated research processes (a participatory and place-based methodology). Holding space for multiple perspectives and seeing value in multiple teachings through respectful individualism is an adaptive feature of many Indigenous knowledge systems (Berkes 2018) and it is a principle that is shared across many Indigenous groups, as was made evident by the plurality of models for knowledge coexistence (**Section 3.5**). This may be why Two-Eyed Seeing and other Indigenous knowledge co-existence frameworks seem to be so readily embraced by Indigenous knowledge holders and community members (Bartlett et al. 2012) where there is perhaps less of a paradigm shift required "to use both these eyes together" than for those that ascribe strictly to a Western scientific tradition.

The case studies also highlight some challenges that need to be overcome if conventional fisheries management and research are to embrace Two-Eyed Seeing. The Slave and Saskatchewan River Delta case studies, while both very successful, are relatively small in scale compared to the spatial extents of many fisheries. Perhaps part of their success is because they are localized, each clearly linked with specific Indigenous management areas, and about mostly FSC fisheries. The success of Two-Eyed Seeing in these case studies illustrates that it can be done in small-scale fisheries that have to date largely been ignored by conventional fisheries management and science. The American eel case study, with commercial interests, has been more challenging (Giles et al. 2016), and has focused on one small part of the eel's range. To fully embrace the concept of Two-Eyed Seeing at the same scale as the range of fish species, fisheries, and/or management areas, would require coordination of many Indigenous peoples and other interests spanning many governments and knowledge types. Such possible mismatches of scale for some species and fisheries may be an obstacle to the uptake of Two-Eyed Seeing for commercial fisheries that focus on wide-ranging species. However, examples do exist demonstrating how such frameworks can and have led to legislated spatial closures for larger scale commercial fisheries (Ban et al. 2018). But even if most initial examples of Two-Eyed Seeing in fisheries are relevant to small-scale fisheries, improvement in such fisheries is needed (Hilborn et al. 2020) and much learning can come from such case studies and lead to future attempts to apply Two-Eyed Seeing more broadly to commercial and industrial fisheries.

A useful thought exercise at this stage is to conceptualize how this vision could be applied to a specific fishery or other aquatic issue (*e.g.*, development of species at risk recovery plan; siting of a protected area). How would a relativist ontology, pluralistic epistemology, value-centered axiology, and participatory and place-based methodology change the context's current and future state? How would linked practices and policies reflect the interdisciplinary, cross-cultural, and pluralistic nature of Two-Eyed Seeing? This exercise could veritably provide a study unto itself, and so for the purposes of the present argument, we can instead take the existing groundwork that has been laid by Giles and colleagues (2016) who put forward a set of recommendations to improve Mi'kmaq input into the current Western-dominant approach to American eel fisheries and their management. Specifically, they lay out many eeling practices (*e.g.*, sharing eels with Elders, family, and community members; being highly selective during summer eeling) and corresponding management recommendations (*e.g.*, minimum FSC level ensured; size limits for summer eeling, respectively) that they wish to be reflected in the forthcoming update to the American eel Integrated Fisheries Management Plan (IFMP) for the Maritimes region of Canada. The Department of Fisheries and Oceans Canada (DFO) is currently in negotiations with various Indigenous organizations and communities to update the IFMP appropriately, and the authors flag this as an "opportunity to explore the complementarity among the First Nations and Western scientific approaches to management while allowing for the value systems and beliefs among the different knowledge systems to be respected" (Giles et al. 2016).

It is critical to note, however, that the differing worldviews underpinning Mi'kmaq and Western decision-making processes currently produces distrust and frustration on both sides, and while the authors still see "considerable opportunity" for Two-Eyed Seeing in this context, there may be many comparable cases where such an approach is wholly inappropriate to apply. For instance, as Indigenous Nations increasingly return to self-determination, there needs to be a commensurate rise in the state's confidence in the capacity of these peoples to "manage" fisheries without federal oversight (or that of another colonial force). This relinquishing of power to Indigenous process and management rights is also imperative as many post-colonial nation states grapple with reconciliation. Two-Eyed Seeing will never fit a context in which both sides are not willing partners, which may well be the case where Indigenous Nations exercise fishing rights legislated constitutionally, in treaties, and/or through international legal norms (*e.g.*, the United Nations Declaration on the Rights of Indigenous Peoples, UNDRIP Articles 25, 32.2, and 32.3).

Along a similar vein, cases may often arise where predictions and/or results are incongruent or unaligned. For instance, in both Mantyka-Pringle et al. (2017) and Abu et al. (2019), water quality was found to be in a 'worse' state based on Indigenous knowledge indicators compared with Western scientific indicators which graded water quality more moderately. A viable explanation for this trend is that through a Western scientific lens water with levels of chemical contamination below a certain threshold is considered safe to drink (a universal truth based on objectivism), whereas through an Indigenous knowledge lens, any departure from a past known state is being noted so the substantial changes in water quality being signposted by Elders is strongly suggesting otherwise (Mantyka-Pringle et al. 2017). Such discrepancies are in fact informative as they provide a fuller understanding of a complex system where Indigenous knowledge systems may exhibit higher sensitivity to environmental perturbation making them early detectors of ecological change (Berkes 2018). Though not generally supported by the case studies presented herein, there may of course be instances where predictions or results point in completely opposing directions – but, as with northern pike in Abu et al. (2019), these disconnects may again be illuminating and indicative of multiple realities existing within a system (*e.g.*, where a high local abundance is being reported by local knowledge holders, and few fish landings are being reported coincident with declining commercial interest in this species). In many cases, access to multiple knowledge types may itself be a luxury, and drawing from multiple evidence bases may be the only means of filling critical knowledge gaps (*e.g.*, as with vegetation indicators in Abu et al. 2019). Additionally, some Nations may choose not to engage with colonial governments due to histories of violent colonization, and resulting relationship fractures and distrust.

Conflicting interpretations of recent events and information abound in complex fisheries systems (*e.g.*, Newfoundland's northern cod (*Gadus morhua*, Gadidae) fishery; Finlayson 1994), and if we continue to subscribe to the notion that knowledge is free from social process, or that scientific interpretations are not socially constructed to a large extent, then we are choosing to uphold the *status quo* or Western approach to fisheries research and management that has led us to this current state of many fisheries failing both ecologically and socially (Pauly et al. 2002). Rounding out our understanding and approach to fisheries to include other knowledges and ways of knowing is no longer an issue of awareness or method, as exemplified here, but rather the barriers are time (to build the requisite relationships), a general lack of incentives (little provocation away from inaction), and entrenched systems of political power or unsubstantiated perception of knowledge hierarchies. As common in co-management schemes (Chuenpagdee & Jentoft 2007), the precursor to each case study was environmental perturbation followed by a need for innovative approaches to understand and manage the aquatic environment – are we then to wait for the global disruption of all fisheries, large and small, before we choose to depart from the safety of the *status quo*? Our collaborative departure from this *status quo* can instead be a shared choice – an action imperitive – generated through an equitable Two-Eyed Seeing approach which leverages many tools and perspectives towards imagining better futures for fisheries and humanity.

3.8 Conclusion

Two-Eyed Seeing offers a legitimate, decolonial approach for working on “wicked” fisheries problems or other aquatic environmental challenges where singular solutions are near impossibilities, and emphasis must instead be placed on engaging in “interactive communication and learning among stakeholders, where norms and values are played out and where different ethics, ideologies, and epistemologies are active” (Jentoft & Chuenpagdee 2009). Through its action imperative and cooperative foundation, Two-Eyed Seeing values collective over individual action as well as collaborative learning or ‘co-learning’ (Bartlett et al. 2012) where once disparate and polarized groups or knowledge holders are united, bringing together their respective understandings, insights, and skills to bear on a common or shared problem. They learn from one another and in doing so produce a collectively enriched picture of a complex system. Two-Eyed Seeing is a framework that very much centers on *process* rather than *outcome* and it is actualized in its unending pursuit of responsibilities to those beings – all beings – now as well as seven generations ahead (McMillan & Prosper 2016). Improving how fisheries and aquatic ecosystems are studied and managed would not be an end point *per se*, but rather a transformative and ongoing action that can be brought about through Two-Eyed Seeing that remedies power relations, respects differences, and upholds unique strengths instream with its uniting of knowledges and ways of knowing. The approach outlined here also has tremendous merit and relevance to other complex environmental problems or issues beyond the aquatic realm, and we challenge our readers to personally take on the action imperative of applying the Two-Eyed Seeing framework to the context – fisheries, aquatic, or otherwise – in which they study, work, and live.

3.9 Figures

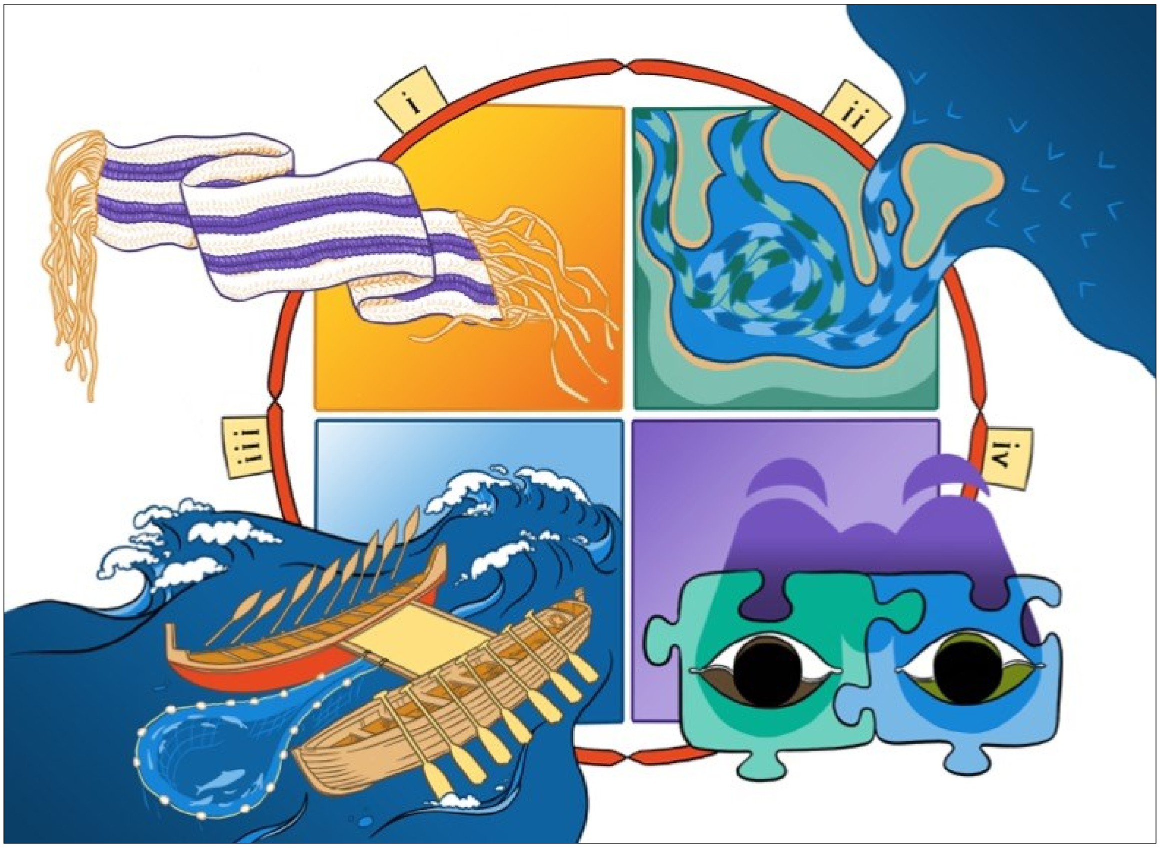


Figure 3-1 Indigenous conceptual frameworks for promoting knowledge coexistence. These include: (i) the 'Two Row Wampum' or Kaswentha in Haudenosaunee; (ii) the 'Two Ways' or Ganma in Yolngu; (iii) the 'Double-Canoe' or Waka-Taurua in Māori; and (iv) 'Two-Eyed Seeing' or Etuaptmumk in Mi'kmaw. Refer to main text (Section 3.5) for full descriptions of each framework (subsections (i)-(iv), respectively). Artwork by Nicole Burton.

Figure 3-2 Map of Canada illustrating the location of the three case studies operationalizing Two-Eyed Seeing.
These include: (A) Slave River Delta; (B) Saskatchewan River Delta; and (C) *Unama'ki*/Cape Breton. The landmass depicted here involves complex intersections of Indigenous territories and language groups with similarly diverse place names—we present names in English only because we cannot do this diversity justice in the scope of this diagram. Refer to main text (**Section 3.6**) for full descriptions of each case study (**Sections 3.6.1-3.6.3**, respectively). Artwork by Nicole Burton.

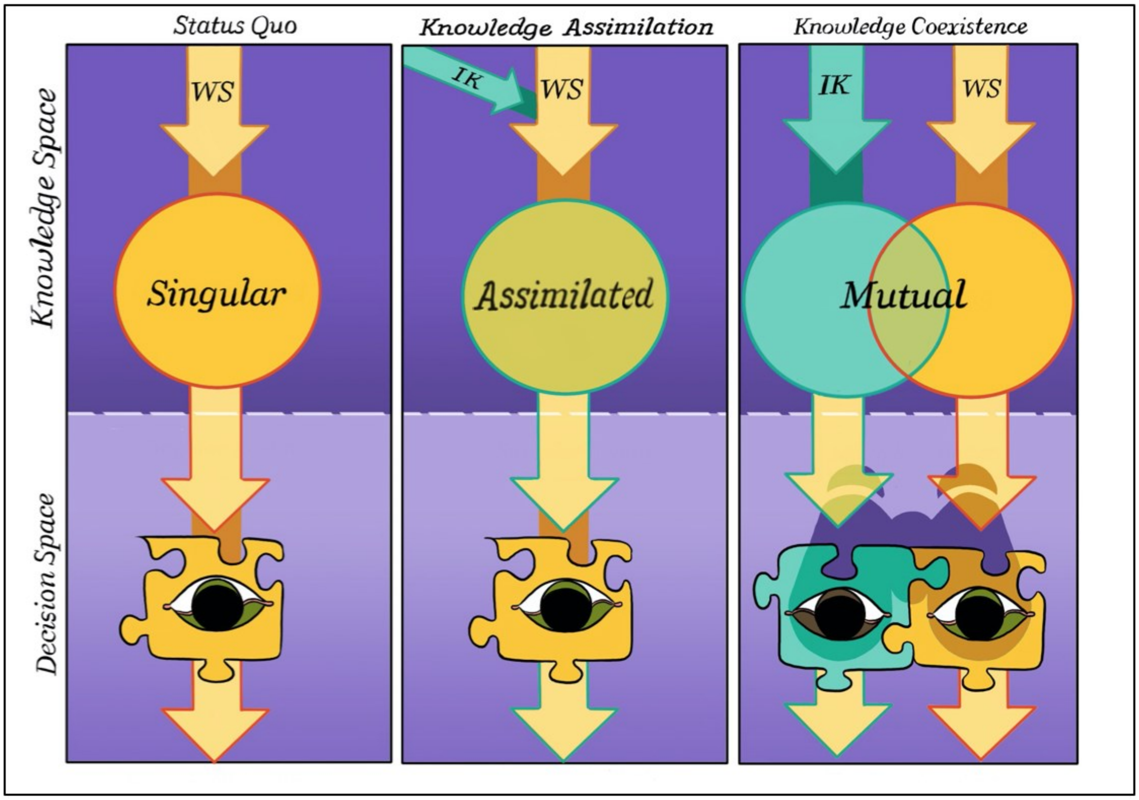


Figure 3-3 A conceptual framework detailing the flow of knowledge (WS = Western science; IK = Indigenous knowledge) that underpins researchers' understandings or views of reality, and ultimately guides their research and management decisions, as classified under three main archetypes. Status Quo (left) depicts a "one-eyed" approach that accepts solely Western science as a valid knowledge system, producing a singular understanding that informs decision-making. Knowledge Assimilation (center) is typical of many management approaches that incorporate Indigenous knowledge into Western science for an improved understanding to inform decision-making, ultimately producing another "one-eyed" approach (however, the reverse situation can also occur whereby Indigenous peoples utilize Western scientific approaches to inform their decision-making that is guided principally by Indigenous knowledge; also "one-eyed" but in the inverse orientation). Lastly, Knowledge Coexistence (right) shows an approach where Western science and Indigenous knowledge contribute in parallel to produce a mutual understanding from which context-specific decisions are formed – this reflects an approach that is congruent with Two-Eyed Seeing (represented here by the same symbology shown in Figure 3-1). Artwork by Nicole Burton.

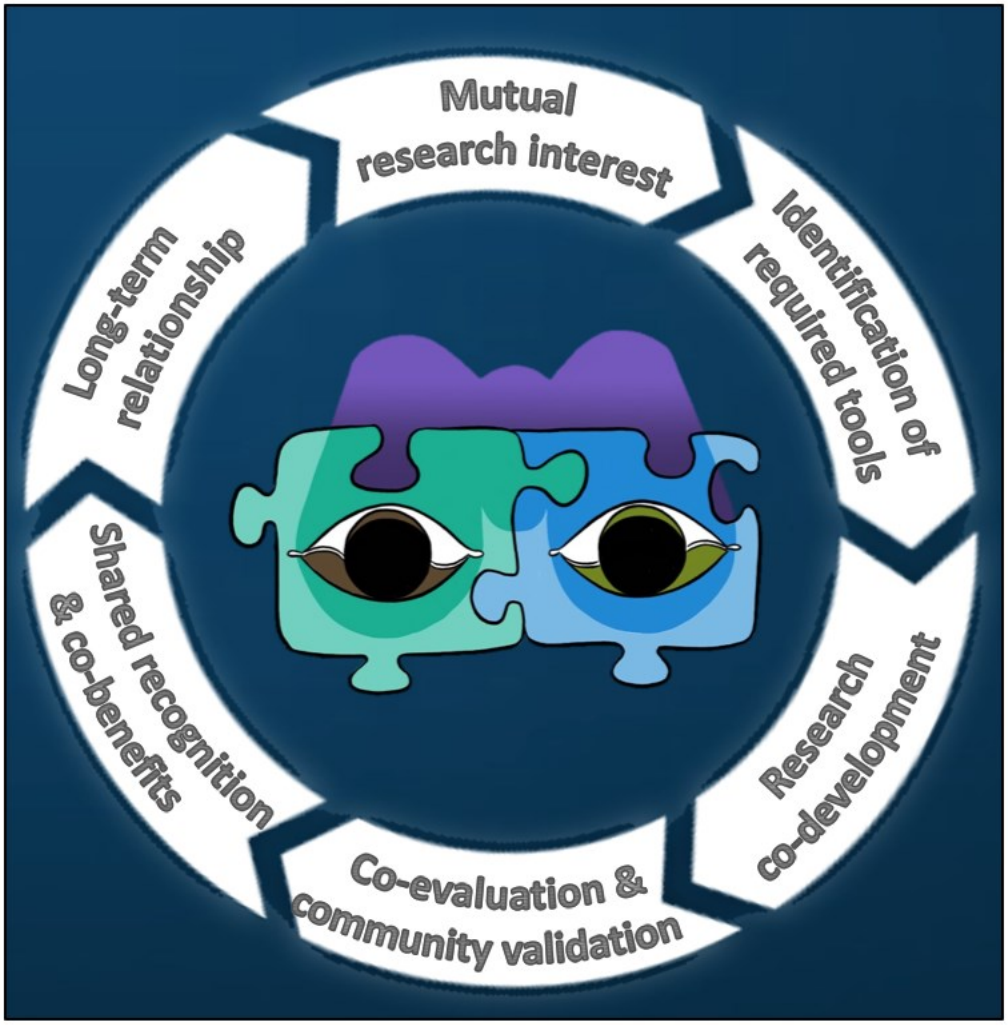


Figure 3-4 A stepwise framework for applying Two-Eyed Seeing to research, reflecting a summary of beneficial steps taken in three case studies explored herein.

3.10 Tables

Table 3-1 Glossary of key terminology.

English term (abbreviation)	**Indigenous term (language; area)**	**Definition (source)**
Double-Canoe	*Waka-Taurua* (Māori; Aotearoa/ New Zealand)	A conceptual framework formalized in 2018 for unifying knowledges and ways of knowing, especially Western and Māori. It is described as "two canoes... lashed together... each canoe represents the worldview and values of the people who are coming together to achieve a common purpose... each group is inherently different, and the knowledge, values and actions of each, are not made to fit into the other."[1]
Indigenous Knowledge (IK) or Traditional Ecological Knowledge (TEK)	*	A cumulative body of knowledge, practice and belief evolving by adaptive processes and handed down through generations by cultural transmission, about the relationship of living beings (including humans) with one another and with their environment (from Berkes, 2018). It is not separable from the knowledge holders/keepers or the environment in which it is embedded.[2]
Māori Guardianship	*Kaitiakitanga* (Māori; Aotearoa /New Zealand)	"Reciprocal care between Indigenous-Māori people and their territorial environment" – 'Kaitiaki' means guardian, and 'tanga' is a common suffix akin to 'ship' (as in 'kinship' or 'relationship').[1,3]
Mi'kmaq Sustainability	*Netukulimk* (Mi'kmaw; Eastern Canada)	"Achieving adequate standards of community nutrition and well-being today without jeopardizing the integrity, diversity, or productivity of the environment for the future" – for seven generations to come.[4,5]
Plural Coexistence	*	"A model of cross-cultural relations that acknowledges and respects Indigenous ontologies, or ways of being, and at the same time is attentive to the historical and current dominance of Eurocentric thinking within natural resource management."[6,7]
Two-Eyed Seeing	*Etuaptmumk* (Mi'kmaw; Eastern Canada)	The gift of multiple perspectives; a conceptual framework coined by Mi'kmaw Elder Albert Marshall in 2004 for unifying knowledge systems. It is described as "learning to see from one eye with the strengths of Indigenous knowledges and ways of knowing, and from the other eye with the strengths of Western knowledges and ways of knowing, and to use both these eyes together, for the benefit of all."[8]

Table 3-1 Continued.

Two Row Wampum	*Kaswentha* (Haudenosaunee; Central Canada)	A 17th century treaty belt to record an agreement between the Haudenosaunee Confederacy and Dutch settlers. "It consists of two rows of purple beads separated by rows of white beads. The purple rows represent the different vessels of the Dutch (a ship) and the Haudenosaunee (a canoe) travelling side-by-side down the "river" of existence (the white beads). While the two vessels remain separate (*i.e.*, the cultures remain distinct), the people from each vessel are meant to interact and assist each other as need be." (from McGregor, 2004b).[9]
Two Ways	*Ganma* (Yolngu; Northern Territory, Australia)	A metaphorical concept of how to mix knowledges equitably and achieve meaningful two-way collaborations. "It relates to the separateness of fresh water and salt water knowledge even at the point where they meet and mix. It is like what some [non-Indigenous people] call a "dialectical" relationship, in which two opposed patterns of ideas complement, interact and relate to one another, but never lose their distinctiveness as separate and opposed parts of one whole."[10]

Sources: [1](Maxwell et al. 2019); [2](McGregor 2004a); [3](Roberts et al. 1995); [4](McMillan & Prosper 2016); [5](Prosper et al. 2011); [6](Howitt & Suchet-Pearson 2006); [7](Zanotti & Palomino-Schalscha 2016); [8](Bartlett et al. 2012); [9](McGregor 2004b); [10](Muller 2012).

Table 3-2 Legal and practical imperatives for involving Indigenous knowledge systems in mainstream research across various scales – on the levels of institutions, Indigenous nations, nation states, as well as internationally.

Imperative	Scale	Source	Policy / Call to Action*
Legal: specific instruments stipulating respect for and/or inclusion of Indigenous knowledge in research, teaching, and more generally.	Global (148 UN member states)	United Nations Declaration on the Rights of Indigenous Peoples (UNDRIP; UN General Assembly, 2007)	• Respect that Indigenous knowledge contributes to sustainable and equitable development, and proper environmental management [Guiding Principle] • Indigenous peoples have the right to maintain, control, protect, and develop their knowledge, sciences, and intellectual property over such [Article 31]
	National (Canada)	Truth and Reconciliation Commission (TRC; Government of Canada, 2015)	• Provide necessary funding to post-secondary institutions and Aboriginal schools to bring Indigenous knowledge and teaching methods into classrooms [Actions 62.2 and 62.3]
	Indigenous Nation (Haíłzaqv Nation)	Haíłzaqv Integrated Resource Management Department (Haíłzaqv Nation 2015)	• All research questions and activities in Haíłzaqv territory will be framed to involve Haíłzaqv knowledge [Guiding Principle] • All research will acknowledge Haíłzaqv as an integral part of ecosystems [Guiding Principle]
Practical: requirements for obtaining approvals and/or funding to develop Indigenous-related research projects.	Global (192 UN member states)	Intellectual Property and Genetic Resources, Traditional Knowledge and Folklore (WIPO, 2010)	• Recognize value of Indigenous knowledge (social, economic, intellectual, scientific, ecological, commercial, educational); of equal scientific value as other knowledge systems [Policy Objective 1] • Respect contribution of Indigenous knowledge to conservation, food security, sustainable agriculture, progress of science and technology [Policy Objective 2]
	National (Australia)	Guidelines for Ethical Research in Australian Indigenous Studies (AIATSIS, 2012)	• The rights (as laid out in UNDRIP *Article 31* above) of Indigenous peoples must be upheld and recognized [Principle 2] • Researchers must have a good understanding of the nature of Indigenous knowledge systems and intellectual property [Principle 4]
	Institutional (Canadian universities)	Ethical Conduct for Research Involving Humans (CIHR, NSERC, and SSHRC, 2018)	• Engagement with Indigenous communities is an integral part of ethical research involving Indigenous peoples [Premise] • Researchers should appropriately engage Indigenous communities to involve knowledge holders and systems in research [Article 9.15]

*Policy articles and calls to action were paraphrased for brevity; meanings or implications remain unchanged.

Table 3-3 Philosophical assumptions historically underpinning conventional and Indigenous fisheries approaches and worldviews.

Paradigm dimensions	Conventional fisheries	Indigenous fisheries
Purpose	Fishing-as-business	Sustainable livelihoods; collective well-being
Ontology	Realist; one knowable reality	Relativist; multiple socially constructed realities
Epistemology	Objectivist; empirical truth	Intersubjective; multiple forms of knowledge
Axiology	Values excluded; influence denied	Values included; centre relational accountability
Methodology	Experimental; top-down	Participatory and knowledge-inclusive; place-based
Worldview	Control nature; utilitarian	Humans indivisible from nature; relational

Sources: Adapted from Held (2019) and informed by Berkes (2001, 2003).

Chapter 4: Combining Indigenous and Western fisheries sciences links ultimate fate of sockeye salmon bycatch with conditions of commercial capture and release

4.1 Abstract

Colonial intrusions have shifted Pacific Salmon fisheries from being Indigenous-governed and often terminal to federally-managed and predominantly marine, where a mixture of co-migrating species and stocks—both healthy and vulnerable—are captured together. A selective fishing policy has therefore been instated to permit the capture and retention of certain salmon species or stocks while mandating the release of others as bycatch. A lack of knowledge of how this practice contributes to *en route* mortality in salmon bycatch, however, has precluded accounting for these effects in current management models. Here, we adopt a collaborative learning approach that is strengthened by its reliance on knowledges and methodologies from both Indigenous and Western fisheries sciences to provide a first estimate of release mortality for sockeye salmon (*Oncorhynchus nerka*) bycatch on the North Coast of the land now called British Columbia, Canada. With commercial fishers, we simulated a purse seine fishery with sockeye salmon bycatch where we assessed and radio-tagged each individual prior to release. By partnering with First Nations fishers and fisheries managers up-river, we then monitored post-release fate using biotelemetry, genetics, physical recaptures at multiple points along the migratory path, as well as *via* a fisheries tag return program. Based on these varied lines of evidence, we find 25% mortality for tagged sockeye belonging to the adjoining Nass River, and survival analyses reveal higher mortality risk for Sockeye that spent prolonged periods of time in

the seine net (30–45 min versus <15 min), were female, and had damaged fins. A release mortality estimate has since been applied for the first time to the management of North Coast seine fisheries, ensuring that the impacts of these fisheries for wild Pacific salmon are not underestimated.

4.2 Preface

The work described herein represents the coming together of Western-trained fisheries scientists and practitioners, some of whom are Indigenous (belonging to the Nisga'a [AJR] and Gitxsan Nations [TLW]), with Indigenous community partners (principally the Nisga'a Nation) on the North Coast of the land now commonly known as British Columbia, Canada. Indigenous knowledges, as well as ways of knowing and being, are foundational building blocks from which this work stems, and we present conclusions herein that are informed by a rigorous experimental design and analysis that was jointly carried out and evaluated by the collaborative authorship team.

4.3 Introduction

"We conceptualize an 'Indigenous knowledge' as a body of knowledge associated with long-term occupancy of a certain place. Indigenous knowledges are unique to given cultures, localities and societies ... They deal with the experiential reality of the world. They are forms of knowledge that reflect the capabilities, priorities, and value systems of local peoples and communities. An important dimension ... relates to how traditional forms continue to emerge and coexist in diverse situations and settings as part of a local people's response to colonial and imperial intrusions." –(Dei 2000 pgs. 6 & 19)

The usurpation and dispossession of Indigenous lands and waters has profoundly reshaped the lived realities of Indigenous Peoples around the globe (Indigenous Circle of Experts 2018). In many cases, these acts have disrupted long-standing relationships of interdependence and responsibility between people, place, and the natural world (United Nations General Assembly 2007). This disruption is palpable on the Northwest Coast of North America where fisheries for Pacific salmon (fish known by a host of Indigenous names throughout their extensive range, such as 'hoon' in the Nisg̱a'a language; genus *Oncorhynchus*) have undergone tremendous transformation since colonization (Newell 1993; Harris 2001). Arguably, nowhere is the opportunity greater for improved and collective management (co-management), collaborative learning (co-learning), and relationship (re)building than in these very fisheries.

Salmon–people relationships have existed in Northwestern North America since time immemorial, and continue to exist, bound to the cultures (Garibaldi & Turner 2004), food systems (Chan et al. 2011), economies and institutions (Trosper 2002) of Indigenous Peoples from California to Alaska, not by chance, but rather through deliberate and sophisticated systems of management and stewardship (Haggan et al. 2006; Turner & Berkes 2006). To maintain high salmon abundance over millennia (Campbell & Butler 2010), Indigenous communities here created context-specific harvesting technologies (*e.g.*, fish traps, dipnets, weirs, seines; White 2006, Moss 2013) and practices (*e.g.*, selective harvesting, spatio-temporal fishing restrictions, egg translocations; Jones 2004, Langdon 2006, Robinson 2008) in accordance with traditional laws, languages, and worldviews. Increasingly, the role of Indigenous Peoples as active stewards of salmon (and indeed other fisheries, and even whole ecosystems; Deur and Turner 2005, Anderson 2013) is being made visible in the academic literature (*e.g.*, Menzies 2006, Lepofsky and Caldwell 2013, Berkes 2018), but the commensurate recognition of these knowledge–practice–belief complexes (*i.e.,* Indigenous knowledges) as 'Indigenous fisheries *science*' (or more broadly 'Indigenous science') is only in its infancy.

Industrial commercial fisheries for Pacific salmon emerged in the late 19th century, revolutionizing the scale of fishing activities, the methods used, and ultimately the relationship between salmon and people. Top-down regulations imposed by colonial governments swiftly displaced and criminalized many Indigenous fishing activities (*e.g.*, Canada's ban on freshwater, net-based fisheries in 1878; Harris 2009), favouring harvest in marine systems due to the logistic ease and high value of capturing adult salmon at the end of their marine phase, before they initiate upstream migration to spawning grounds, during which they support critical food fisheries. Under this new paradigm, salmon are subject to highly centralized corporate management systems applied over vast geographic areas, with the majority of salmon in British Columbia (BC) now caught in marine approach waters (Walters et al. 2019). Commercially targeting salmon in marine approach waters, before they have segregated to their natal rivers and streams, places substantial pressure on co-migrating species and populations (or 'stocks') potentially not of sufficient abundance to sustain exploitation (Healey 2009; Nesbitt & Moore 2016).

Through the colonial *Fisheries Act* instrument, the management of mixed-stock salmon fisheries has been primarily the purview of the federal department of Fisheries and Oceans Canada (DFO), with limited input and direction from First Nations, with the main mechanism for co-management in many cases being Integrated Fisheries Management Plans (IFMPs). DFO's priority in managing with a "precautionary approach" is first to meet conservation targets, then to support Indigenous Food, Social, and Ceremonial (FSC) fisheries, followed by economic opportunities, in that specific order (Nelson et al. 2004). By permitting marine commercial fisheries for salmon ahead of their re-entry into rivers to spawn (and be utilized for food fisheries *en route* to spawning grounds), places tremendous pressure on Canada to meet its FSC obligations in managing under the precautionary approach framework. The upstream consequences of marine commercial fisheries in terms of associated bycatch and mortality impacts are often major unknowns and thus cannot be accounted for in management models and practices.

Through an Indigenous knowledge lens, it is our view that by not fully understanding the intricacies of salmon runs and the places they return to, by not carefully paying attention to entire ecosystems and relationships throughout salmon migrations, by shifting from regenerative to productionist thinking, by removing the bodies of Indigenous Peoples from salmon and river governance, colonial management regimes have failed to sustain the healthy relationship with salmon that is necessary for continued co-existence, and this is evidenced by poor and/or unpredictable salmon returns in recent years and decades. Colonial management structures are beginning to see shortcomings in imposed management systems, and there has been a perceptible shift (from a local to national scale) towards recognizing Indigenous fisheries managers and knowledge keepers as *experts* who have created bodies of knowledge from which current understandings of system dynamics have been built (McMillan & Prosper 2016; Thompson et al. 2020). Co-management, with a refocus on Indigenous priorities and expertise, calls for a restructuring of the corporate management system of BC salmon fisheries—one where Indigenous communities are not only part of the fisheries management structure, but one where leadership actually returns to the hands of community (*e.g.*, the Indigenous-led joint fisheries management approach being developed by the Central Coast Indigenous Resource Alliance as a replacement for IFMPs; CCIRA 2020).

To confront the challenge presented by capturing healthy salmon populations alongside more vulnerable ones—which is essentially unavoidable in marine approach waters where salmon co-migrate—DFO's proposed solution centers on dealing with acceptable levels of harm, focusing on the prescribed release of salmon stocks of concern "alive and unharmed" (as outlined in DFO's policy for *Selective Fishing in Canada's Pacific Fisheries*; Fisheries and Oceans Canada 1999) in order to maintain the exploitation of healthier populations. This policy stands in stark contrast to many Indigenous knowledge and governance systems that position salmon as relatives, not resource, and that have long centered on relationship-based approaches to management, and which have manifested in a widespread "keep what you catch" ethic where the return of captured fish to the water is a sign of disrespect and thus not part of ethical fisheries practice (Berkes 2018). This selective fishing practice therefore provides one example where co-management in terms of cultural beliefs is not being met, where Indigenous knowledges and perspectives are not reflected in the presiding management scheme.

What is needed in many systems—in the absence of a large-scale return to regenerative approaches—is a fuller understanding of the implications of this selective fishing policy in the context of marine mixed-stock fisheries. Prior to the work described herein on BC's North Coast, a mortality estimate linked to this selective fishing practice was not accounted for in the management models used to govern the fishery. The best actionable way forward is thus to use the best tools at our disposal to fill a critical knowledge gap—mortality linked to the incidental capture and release of salmon—in service to our salmon relatives. Here, we establish a collaborative partnership that brings together fishers and managers from the commercial fishery, DFO, and Indigenous communities and governing bodies to estimate salmon release mortality to inform management practices.

4.4 Study Context

In Portland Inlet—Fisheries Management Area 3 on BC's North Coast—a large commercial fishery operated by the Canadian Fishing Company (Canfisco) targets co-migrating salmon in these marine approach waters before they reach Indigenous fisheries in-river. The adjoining K'alii Aksim Lisims (Nisg̲a'a for 'Nass River'; used hereafter) has provided for the "People of the Nass River"—the Nisg̲a'a Nation—for millennia. The Nisga'a Nation is the only First Nation in the area with an official treaty (*Nisga'a Treaty* 2000; BC's first modern-day treaty, and one of only four ratified treaties out of ~200 First Nations in the province), which involves a specific right to fish for salmon. The Nisg̲a'a Fisheries and Wildlife Department (NFWD), who co-manage the Nass River salmon fishery with BC and Canada (*via* DFO) as outlined by the Nisg̲a'a Treaty (2000), run a renowned fisheries science program that has been used for Nass salmon assessment and management for now nearly three decades (est. 1991). Due to climate change as well as other anthropogenic or environmental stressors adversely affecting salmon, there is now growing concern for threatened Nass salmon populations, such as Kwinageese River Sockeye in the Upper Nass River Watershed (**Figure 4-1**) who suffered severe declines following a habitat blockage in 2011 (Gaboury et al. 2015).

Selective fishing is therefore now used in Area 3 such that Pink salmon (*O. gorbuscha*) can be harvested within the 'margins of allowable harm' for co-migrating Sockeye. As levels of allowable harm vary among Sockeye populations, this practice intends to allow harvest of some Sockeye, while providing some degree of protection for others by mandating the release of all Sockeye during the anticipated passage time of more vulnerable stocks such as Kwinageese. In 2016, the year of this study, 495 Sockeye were retained by the commercial seine fishery during a single permitted opening for Sockeye, and >46,000 Sockeye were incidentally captured and released by seine fisheries targeting pink salmon (**Table 4-1**).

Working with Canfisco and NFWD in this study, our collaborative team designed and executed the first assessment of "ultimate fate" of seine-released Sockeye in Area 3. Ultimate fate goes beyond immediate or short-term assessments of mortality or sublethal effects to holistically monitor the entire migratory journey of salmon. Assessing ultimate fate better reflects a primary concern of Indigenous Peoples throughout the region, and that is the successful arrival of salmon on spawning grounds where they give rise to the next generation. For this work, Canfisco facilitated the charter of purse seine vessels to simulate the incidental-capture-and-release experience for Sockeye who we radio-tagged prior to release and then tracked to spawning grounds. To yield insight into how Sockeye fare over the course of their migration, as well as to ground-truth biotelemetry findings, NFWD made available their in-river monitoring platforms (*i.e.,* Nisga'a Fishwheels (see Box 1), Meziadin Fishway; **Figure 4-1**) through which tagged sockeye could be recaptured, reassessed, and released. Few such studies have monitored on such a comprehensive scale given the inherent logistical challenges of recapturing wild salmon at multiple points along their migration path—a feat that would not have been realized without the generous sharing of knowledge and methodologies by our partners. The methods and analyses that follow, while clearly steeped in a Western scientific tradition, were informed, permitted, and facilitated by partnering Indigenous knowledge holders—ultimately strengthening both the approach taken and the impact and importance of the work at hand.

Box 1: Nisga'a Fishwheels

Fishwheels have been employed by Indigenous Peoples since pre-contact times, first constructed from cedar and nettle fiber, now made of aluminium and nylon mesh (Menzies 2006). They are located in-river, powered by the river's current, operating much like a watermill except in the place of paddles are baskets that scoop up water and fish ascending the river (principally salmon; Snively and Corsiglia 2001). As the baskets rise, the fish slide into submerged holding pens (see **Figure 4-2**) where they remain until released unharmed by those monitoring the fishwheel, or retained for food as recounted by Nisga'a Sim'oogit (Chief) Eli Gosnell: *"the flowing river kept salmon alive until they were either harvested or released, we always took only the fish we needed and no more"* –(as quoted in Menzies 2006). For nearly three decades, the Nisga'a Fisheries and Wildlife Department has been using fishwheels as a platform for stock assessment and monitoring by combining this technology with modern statistical methods and research tools such as mark-recapture methods and genetic analyses stemming from trough-based tagging and sampling performed right on the fishwheels.

4.5 Methods

4.5.1 Fish Capture, Tagging and Release

Between July 22 and August 6, 2016, during the peak passage of the Kwinageese stock through marine waters, we worked aboard the commercial purse seine vessels "Ocean Venture" and "Ocean Virtue" (operated by Nisga'a commercial fishers) on days where Area 3 was closed to commercial fishing. Captains and crews operated their vessels under our scientific research permit (DFO, XR 226 2016) to simulate a commercial fishery for pink salmon with sockeye bycatch—except engineered in reverse, with pink salmon and all other intercepted species being released immediately, and instead sockeye salmon were retained for further study prior to release. All protocols followed typical fishery operations as the vessels, crews, knowledge bases, gears, and methods used were precisely those already engaged in the commercial purse seine fishery in Area 3.

Our study was conducted in tandem with a separate 'sister' study on chum (*O. keta*) bycatch (see Cook et al. 2018b) for a complete overview of purse seine vessel operations). To obtain sockeye, fish were captured in strategic locations by seine net (549 m long; 55 m deep; 100 mm bunt mesh) which was then 'pursed' alongside the vessel to allow for a brailer (a large dip net operated by a hydraulic winch) to transfer fish on deck for sorting. Fish were held in the submerged net for a 'moderate' (<15 min) or 'prolonged' (30–45 min) amount of "net time" prior to brailing to simulate sorting times characteristic of capturing small (<300 fish) and large sets of fish, respectively, which we might expect to encounter during low versus high return years. Once on deck, all non-sockeye were released and all Sockeye were transferred first into large flow-through totes, and then individually dipnetted out and placed into a foam-lined, flow-through, V-shaped trough for various assessments, tissue biopsies, and tagging prior to release. All associated times (*i.e.,* fish being sorted, in tote, in trough) were recorded. Protocols adhered to an animal care and use permit to minimize any harm and distress for all fish involved in the study (University of British Columbia, A15-0205).

Once in the trough, each Sockeye (*N=395*) underwent the same rapid set of procedures led by 2–3 technicians from the research team: (i) sex was determined from secondary sexual characteristics; (ii) fork length was measured (minimum 45 cm; otherwise released); (iii) the number of rayed fins damaged (*i.e.,* frayed or split) was counted; (iv) injury was scored (0–3) based on scale loss and wound severity (where 0 = no injury; 1 = low scale loss (<5%) and/or small surface wounds; 2 = moderate scale loss (5–20%) and/or shallow wound(s); 3 = high scale loss (>20%) and/or exposed flesh); and lastly, (v) the presence/absence of survival-linked reflexes (*a.k.a.* reflex action mortality predictors or 'RAMP'; following Davis 2010, Raby et al. 2012) was tested and scored (from 0 = all reflexes present to 1 = all reflexes absent; see **Table 4-2** for pertinent summary information). Two tissue biopsies were taken: 6 mm from the adipose fin for genetic stock identification (GSI; following Beacham et al. 2004); and 2–3mm from the gill filaments for functional genomic analyses (following (Castañeda et al. 2014)Miller et al. 2011) as part of a separate study (data not presented herein).

Prior to the release of tagged sockeye, we applied an internal transmitter and an external tag for upstream detection and identification, respectively. This provides both a means to monitor survival as fish continue along their migration (or cease to do so) and enables fishers and others to report back any intercepted fish so they can be accounted for. For internal tagging, one technician used a retractable applicator to implant a radio tag

(Pisces 5, 43 mm length x 16 mm diameter, 15.2 g in air; Sigma Eight Inc., Newmarket, ON) inside the stomach of each tagged sockeye *via* oesophageal implantation. This is a rapid and harm-reducing approach (causing no dermal injury as with surgical implantation; and imposing minimal drag as with external attachment; Raby et al. 2015a) which follows well-established procedures (Bridger & Booth 2003; Cooke et al. 2005) and is only made possible because these fish cease feeding prior to freshwater re-entry. For external tagging, one technician inserted a uniquely numbered anchor tag (FD-94; Floy Tag & Mfg. Inc., Seattle, WA) into the dorsal musculature of each fish—another common and passive alternative to more invasive approaches (Drenner et al. 2012). Every effort was made to minimize stress and expedite the amount of time tagged sockeye were handled (all in-trough procedures took place in <2.5 min per fish), after which Sockeye were released overboard to continue their upstream migration as would normally be done with bycatch during actual fishery operations. Previous validation studies by members of our team have revealed that this approach to biopsy and tagging in the marine environment is effective and provides an opportunity to assess the impact of experimental treatments like those described here (Cooke et al. 2005).

4.5.2 Fish Tracking and Recapture

In partnership with NFWD, we carried out a multifaceted effort to monitor for the upstream passage of tagged sockeye. We combined the use of: (i) fixed and mobile telemetry receivers to detect fish; (ii) the Nisga'a Fishwheels and Meziadin Fishway to physically recapture and resample fish; and (iii) an extensive tag return program to incentivize reporting of fish removals through fishery activities.

As fish passed upstream, their transmitters would emit a uniquely coded radio signal (every 3 sec) that would be detected by strategically placed receiver stations (Orion, Sigma Eight Inc., Newmarket, ON; with 3- or 4-element Yagi antennas), informed by the extensive place-based knowledge held by NFWD. Stations 1–3 spanned the Lower Nass River, Stations 4–6 "gated" major spawning areas for Nass Sockeye (Meziadin, Bell-Irving (*en route* to Bowser Lake), and Kwinageese), and Station 7 monitored passage to the largest Sockeye producer in the neighbouring Skeena system (Babine) where some of our mixed-stock bycatch were anticipated (**Figure 4-1**; **Table 4-3**). Many stations were positioned near or directly on in-river monitoring platforms which presented opportunities for physical recaptures or simply re-sighting tagged sockeye: Stations 2 and 3 were adjacent Nisga'a Fishwheels (operated by NFWD technicians; recapture potential); Station 4 was affixed to the jointly-managed Meziadin Fishway (with technicians from NFWD (1), Gitanyow Fisheries Authority (1), and DFO (1); recapture potential); Station 5 was adjacent to the Kwinageese video-counting Weir (NFWD technicians; observation potential); and Station 7 was affixed to the Babine counting Fence (operated by the Lake Babine Nation; observation potential). Finally, opportunistic mobile tracking (by helicopter, by truck, and on foot) also took place in both watersheds (**Table 4-4**).

When Sockeye ascending the Nass River were recaptured by in-river monitoring platforms with recapture potential (*i.e.,* Nisga'a Fishwheels, Meziadin Fishway), trained technicians performed a near-identical suite of procedures as above in flow-through troughs: anchor tag number was recorded; sex, fin damage, and injury were reassessed in the same fashion; and another gill biopsy (again for a separate study) was obtained. RAMP was not reassessed as fishwheel-captured fish are highly vigorous, and an additional adipose fin biopsy was not required (as GSI would not change over migration as genomic signatures might). Technicians repeated this process for 78 randomly selected, non-tagged sockeye to serve as a baseline for comparison. Tagged Sockeye could also be recaptured and harvested by fishers, and thereby removed from the bycatch survival study. From information listed on the radio and anchor tags, as well as posters placed in key areas in the watersheds (*e.g.*, boat launches, fisheries offices), fishers could report the location and details of Sockeye capture to our team and be entered in a reward lottery (an approach used with success in fish tracking studies; Pollock et al. 2001).

All tracking activities took place from the start of tagging procedures (July 22) until the end of the Nass Sockeye migratory period (Oct 14). Telemetry detections were filtered for each tagged sockeye so that those separated by less than 3 seconds (the burst rate) or more than 30 seconds (likely false positives) were removed. An estimated migration path was then built for each fish, where (i) detection, (ii) recapture, and (iii) fisheries capture histories were brought together and plotted over river distance so that information could be cross-validated, and any spurious detections could be inspected and removed. These data were then used to calculate detection efficiencies for each receiver station. The fate of each tagged sockeye was assessed from this combined information, from which we classified individuals as: 1) *ocean mortalities* (OM; = never detected entering natal river); 2) *river mortalities* (RM = detected in natal river but not in natal spawning area); 3) *migration survivors* (MS = detected in natal river and in natal spawning area); or 4) *fisheries removals* (FR = reported removals by fishers, or tags detected during village telemetry scans). Natal areas were determined through confirmation on or near spawning grounds, or, when not found in spawning areas, through GSI analyses. When fish were destined for unmonitored areas based on GSI results, their fate could not be assessed.

4.5.3 Statistical Analyses

Time-to-event analysis—specifically Cox proportional hazards (Coxph) regression—was used to identify the variables that influenced the propensity of tagged sockeye to survive to spawning grounds. Given overall excellent detection probabilities (*i.e.,* high detection efficiencies for fixed receiver stations; **Table 4-3**), Cormack-Jolly-Seber (CJS) models that estimate survival as a function of the probability of detection were not required (Williams et al. 2002). In Coxph, the 'hazard' is an estimation of the rate of a particular event happening (*i.e.,* mortality *en route* to spawning grounds) at a particular point in time (Cox 1972). The explanatory variable of primary interest here was net time (moderate *vs.* prolonged). Sex, fork length, fin damage, injury, reflex impairment, as well as procedure times (fish being sorted, in tote, in trough) were also included as explanatory variables. For survival analyses, ultimate fate (the event of interest) was assigned either a value of 1 (MS) or 0 (OM or RM); FR were censored at their point of recapture. Fate time was specified either as (1) the number of days between tagging and the observed fate, or (2) the distance (in river kilometers) between tagging and the observed fate. The full model (containing all covariates) and all nested models (containing different covariate combinations) were sequentially run using fate time in days first, then repeated using the distance metric. All models were specified as right-censored, fitted using the 'survival' package in R (Therneau 2020), and plotted using the R library 'survminer' (Kassambara et al. 2017).

Model selection was done by minimization of Akaike's information criterion corrected for small sample sizes (AICc) *via* the 'MuMIn' package in R (Akaike 1974; Burnham & Anderson 2002). To compute the sample size required per tagged sockeye population to allow for the comparison of survival curves between treatment groups (moderate *vs.* prolonged; *via* log–rank tests), power analysis was performed using the 'powerSurvEpi' package in R (Qiu et al. 2018). We manually adjusted parameters in the 'ssizeCT' function (power=0.8; type I error rate 'α'=0.05; ratio of individuals in each group 'k'=1) and estimated the number of events expected per group based on prior related work (Raby et al. 2015b; Cook et al. 2018a). Coxph, AICc, and power analysis have all been used in concert in several other recent salmonid survival studies (Frechette et al. 2020; Serra-Llinares et al. 2020).

Given that fin damage, injury, and reflex impairment are ordinal variables that were strongly left-skewed (*i.e.,* many low harm observations), non-parametric rank sum tests were used to examine between-group differences in these sub-lethal effects. Differences of interest included condition at initial capture between net time groups, changes in condition between initial capture and recapture (where applicable), as well as variation between recaptured tagged sockeye and baseline comparators captured at in-river monitoring platforms. Wilcoxon's signed-rank test for paired data was used to inspect intraindividual differences (initial *vs.* recapture), and Mann–Whitney *U* tests were performed to compare interindividual differences (moderate *vs.* prolonged; recapture *vs.* baseline). All analyses (and requisite validations) were performed in R, version 3.6.3 (R Core Team 2017).

4.6 Results

4.6.1 Stock Composition

Experimental commercial fishing activities in this study could indeed be characterized as 'mixed stock'. Purse seine sets (*N=29* over 8 fishing days) captured on average 340 fish (range: 30–1050) and were made up predominantly of pink salmon (76%), followed by sockeye salmon (13%), chum salmon (7%), and a small number of other species (4%). Tagged Sockeye were identified as being primarily of Nass origin (75%), followed by Skeena origin (18%), with a small number destined for other watersheds (4%) or remained of unknown origin (3%; **Table 4-5**). Nass and Skeena Sockeye were comprised principally of their largest producing stocks, Meziadin (69%) and Babine (76%), respectively. The next three largest populations were from the Nass system, and included Kwinageese (12%), Bowser (4%), and Damdochax (4%) which are known to have higher passage proportions in mid-July through the Nass marine area (Gaboury et al. 2015). GSI results suggest that a total of 20 Sockeye that belonged to various populations in the Skeena system were tracked in the Lower Nass River, with 10 individuals showing evidence of fallback (revealed by detections of downstream movement past 2 or more stations after ascending the Lower Nass River). Nearly all individual GSI probabilities were high (*N=131*; mean±SD = 0.96±0.1), with four fish associated with lower probability values (0.4–0.6).

4.6.2 Ultimate Fate

A total of 10 tagged sockeye were reported as captured by marine fisheries, 39 fish were reported from river fisheries (Nass *N=37*; Skeena *N=2*), and 8 fish were detected in communities during permitted village radio telemetry scans (total *N=57*; therefore 14% FR, all between July 25 and September 21, 2016). Given tracking efforts were concentrated in the Nass system, fate outcomes could only be reliably assessed here (see **Table 4-5**).

Based on detection, recapture, fisheries capture, and GSI data, 192 Nass fish were confirmed entering or found on natal spawning grounds (75% MS), 54 were found in river but not in respective natal areas (21% RM), and 10 were never confirmed ascending the Nass River (4% OM). Based on these returns to spawning grounds, a 25% overall mortality estimate can be assumed from fisheries capture and release through to completion of the migration for Nass Sockeye, with variation in mortality (but also sample sizes) across populations, for instance, from 14.2% *en route* mortality for Meziadin Sockeye (of *N=183*, after accounting for fisheries removals) to 41.7% for Kwinageese Sockeye (of *N=36*; **Table 4-5**). After accounting for fisheries removals in the Skeena system, 26 fish were confirmed passing the Babine Fence (Station 7; 50% MS) *en route* to major spawning areas (*i.e.,* Pinkut Creek and Fulton River Spawning Channels; where 11 fish were confirmed through opportunistic mobile tracking). From GSI results, another 26 fish were expected to pass the Babine Fence and are presumed ocean or river mortalities (50% OM+RM), with 11 of these fish belonging to the above-mentioned group of Skeena Sockeye found in the Nass system.

Across Nass populations (and for fish not intercepted and removed by fisheries), prolonged net time (*i.e.,* 30–45 min in the pursed seine net) was associated with lower overall survival (71%) than moderate net time (78%). Both net time groups were equally represented in the 57 fisheries removals (moderate *N=28*; prolonged *N=29*). With power analysis indicating a sample size of 124 fish (62 in each group) needed to detect the expected hazard between net time groups, survival analyses centered on Meziadin Sockeye (moderate *N=93*; prolonged *N=90*) as no other Sockeye populations met this sample size threshold. A total of 26 individuals from this population are presumed mortalities (**Table 4-1**), 18 (69%) of which experienced prolonged net time. Survival curve comparisons show significantly lower survival for female Meziadin Sockeye that experienced prolonged net time (**Figure 4-3A & 4-3C**); the pattern held for males but was non-significant (**Figure 4-3B & 4-3D**). The top five Coxph models evaluated survival over time in days migrating (**Table 4-6**), and included net time (β = 0.92; 95% C.I. = 0.08–1.76), sex (β = -0.80; 95% C.I. = -1.65–0.06), and fin damage (β = 0.40; 95% C.I. = -0.01–0.81) as covariates. All competing models contained subsets of these covariates, with the exception of the fifth-best model (ΔAICc=2.38) which included fork length (β = 0.03; 95% C.I. = -0.09–0.14). The same top five models were identified when rerun using the distance metric, but they carried higher AICc values. The globally highly significant top model shows significantly higher mortality for the prolonged net time group, it suggests a survival advantage for males, and associates higher fin damage with elevated mortality (**Figure 4-4**). The same trends held when survival analyses were repeated for other Nass populations (Kwinageese; Bowser) but the results were less conclusive and non-significant due to low power as anticipated by power analysis.

4.6.3 Sublethal Effects

At the point of initial capture, mean fin damage, injury, and reflex impairment scores were all higher for the prolonged net time group (**Table 4-2**), although a significant difference was only found for fin damage (p = 0.004). Nearly half of Nass fish (*N=147*;

49%) were recaptured at in-river monitoring platforms as tagged sockeye migrated upstream (Nisga'a Fishwheels *N=21*; Meziadin Fishway *N=126*; nine of which were recaptured at both locations). No fish were confirmed *via* observation at the Kwinageese Weir or Babine Fence due to the logistical challenges of spotting external tag numbers by video and for fish passing in high densities. Of the 126 tagged sockeye recaptured at the Meziadin Fishway, now mature with fully developed secondary sexual characteristics (*e.g.*, males: kype and hump presence; females: swollen abdomen), we found that sex was initially mischaracterized for 7 fish, suggesting a 5% error rate in initial sex assignment. No significant differences were found in fin damage or injury scores between net time groups at either point of recapture (all $p > 0.5$), however, fish from the moderate net time group were overrepresented numerically at both the Nisga'a Fishwheels (14:7) and Meziadin Fishway (69:57). Both fin damage and injury scores increased within tagged sockeye between the point of initial capture (mean±SD = 0.54±0.73 and 1.03±0.47, respectively), recapture at the Nisga'a Fishwheels (mean±SD = 1.14±1.35 and 1.29±0.56, respectively), and recapture at the Meziadin Fishway (mean±SD = 1.54±1.43 and 1.33±0.87, respectively). Significant differences in individual fin damage ($p < 0.001$) and injury scores ($p = 0.001$) were found only between the points of initial capture and recapture at the Meziadin Fishway, *i.e.,* neither location differed significantly in these respects from recaptures at the Nisga'a Fishwheels. Finally, baseline comparators (*i.e.,* non-bycatch, non-tagged fish) exhibited significantly lower fin damage and injury scores at both the Nisga'a Fishwheels (mean±SD = 0.08±0.26 and 0.19±0.48, respectively) and at the Meziadin Fishway (mean±SD = 0.64±0.69 and 0.92±0.74, respectively) when compared against respective tagged sockeye groups (all $p < 0.01$).

4.7 Discussion

By simulating a commercial seine fishery in marine approach waters, our collaborative team was able to provide the first assessment of ultimate fate for seine-released Sockeye in Area 3. Our main objective—which was to generate a mortality estimate for Sockeye bycatch in order to inform the management models used to govern the fishery—was reached with success. We found an overall 25% mortality rate for seine-released Nass Sockeye, with 4% occurring before river entry (OM) and 21% occurring thereafter (RM). Since 2016, and as a direct result of this work, a release mortality estimate has been applied for the first time to the management of Area 3 seine fisheries, specifically to the Northern Boundary Sockeye Run Reconstruction (NBSRR) model. An adjusted estimate of 15% release mortality is now used for these stock assessment purposes instead of the 25% recorded in this study to account broadly for the inevitable contribution of unquantifiable mortality factors such as predation, unreported fisheries harvests, and tag-induced mortality. DFO also applies a 15% mortality value in their IFMP program for seine-released salmon (based on historical studies on other salmon species outside of Area 3; Fisheries and Oceans Canada 2020), so the combination of our study and supporting IFMP documentation were both contributing factors to having a mortality value of 15% approved and applied.

Catches are now adjusted, year after year, to account for the unintended mortality caused through the mandated release of salmon. As examples, by adjusting the Sockeye release values in 2016 and 2017 (46,174 and 20,117; **Table 4-1**) to account for 15% mortality, the number of Sockeye now estimated to be subject to seine fisheries mortality in the NBSRR has increased by 6,926 and 3,018, respectively (*Northern Boundary Sockeye*

Run Reconstructions 1982-2017 2018). Rather than considering seine fishery Sockeye mortality as summing to ~500 fish over these two years (**Table 4-1**), the estimated number now surpasses 10,000. These adjusted values are added to what is considered the Total Return to Canada (TRTC) for Nass Sockeye which is then used to determine salmon allocations for FSC fisheries. As defined in the *Nisga'a Treaty* (2000), Nisga'a allocations are set at 10.5% of Nass Sockeye TRTC, which ranges from 16,800 to a maximum threshold of 63,000 fish for small and large returns, respectively. Having the impacts of the marine mixed-stock fishery reflected, at least in part, in the very models from which the TRTC is calculated thus has the co-benefit of ensuring that Nisga'a access to Nass Sockeye is a true proportion of the return as stipulated by the *Nisga'a Treaty* (2000). Not accounting for the mortality observed in a fishery according to the most accurate data and knowledges available—a fishery that already runs counter to the values and practices (*e.g.*, keep what you catch ethic) upheld in pre-existing Indigenous fisheries—would be yet further dismissive of what constitutes ethical fisheries practice for many Indigenous Peoples in the region.

We interpret the rapid uptake of our findings into management (*i.e.,* including before this work was published) as reflective of the way in which the work was carried out. The participatory format and collaborative approach to learning (co-learning) that was practiced throughout the research process helped to build trust among our collaborators, as well as external credibility in our results given that we worked with a diversity of groups engaged in the salmon fishery (similar in some senses to Brownscombe et al. 2019). Our methods also enabled cross-validation and built-in backups. For instance, Sockeye recaptures from the Nisga'a Fishwheels platform ground-truthed biotelemetry detections which can include false positives and noise, or involve equipment that is not as unfailing as the river's current, such that in the event of any outages, fish passage data could still be obtained *via* in-river monitoring efforts. The use of a semi-quantitative injury score was a fundamentally participatory process, relying wholly on Indigenous stewards and technicians when fish were encountered at in-river monitoring platforms, ultimately integrating Indigenous knowledge of fish health and condition into assessments. This type of knowledge, that is the result of "long-term occupancy of a certain place" (recalling Dei et al. 2000), was infused into most every research activity, guiding everything from the timing of the fishery simulation, to the positioning of fixed receiver stations based on anticipated returns, to how we engaged fishers in the tag return program. The strengths of these approaches were then in turn supported by quantitative evidence, for instance in the strategic locations of receiver stations (no major Sockeye population as determined by GSI went unmonitored) and their overall high detection efficiencies (mean 92%, indicative of suitable and strategic placement at each site), to the high reporting rates of fisheries removals (86%, reflective of broad participation and interest from the fishing community). Our results were made strong because they reflect a consensual approach to understanding system dynamics and leveraged (with permission) knowledges and methodologies maintained and protected by our partners.

Given that we are unlikely to see the abandonment of commodity-oriented mixed-stock fisheries under the current corporate management paradigm, this and other research has been positioned specifically at identifying factors that can reduce the harm experienced by released fish—helping to make divergent values systems a bit less dissonant and ultimately improving salmon survival. Here, similar to Cook et al. (2018b), we find evidence that fish who are held for briefer periods of time (15 min or less, consistent with smaller seine sets where fish are held in less crowded quarters) reduces damage and mortality *en route* to spawning grounds. In contrast, sockeye held in the net for prolonged periods (30–45 min, consistent with larger, crowded seine sets that take longer to brail and sort) were found to be 2.5 times more likely to perish before reaching spawning grounds (**Figure 4-3**) and they were also outnumbered among Sockeye recaptures in-river. Concerningly, we found increased mortality among female Sockeye (**Figures 4-3 & 4-4**) which supports the growing evidence base that female salmon are increasingly underrepresented on spawning grounds, with obvious implications for population-level consequences (Hinch & Martins 2011a; Martins et al. 2012; Minke-Martin et al. 2018). Managing salmon based on mortality estimates for females could therefore be an important conservation action, given their essential role in sustaining salmon populations

Finally, all recaptured Sockeye in this study, when compared against control (non-bycatch) Sockeye at in-river monitoring platforms, were significantly more injured—another signal that no fish is ever better off for being handled and lending further credence to minimizing or eliminating capture fisheries that are dependent on fish release measures, and reducing harm to our salmon relatives by every extent possible.

None of this is to say that commercial and Indigenous fishing activities are mutually exclusive. There are, of course, Indigenous fishers employed and engaged in the commercial salmon fishery (such as those operating the Ocean Virtue), with roots in many places dating back to the time of canneries (Newell 1993). Indigenous fisheries can also constitute commercial enterprises, with specific federal programs now in place to encourage Indigenous participation in the commercial fishery since the landmark 1999

Supreme Court of Canada *Marshall Decision* which affirmed a treaty right to hunt, fish and gather in pursuit of a 'moderate livelihood' (R. v. Marshall, [1999]). What we are calling for here is ultimately recognition that colonial forces have profoundly reshaped fisheries for Pacific salmon in present-day BC, and that we stand to enrich salmon management systems through approaches that promote knowledge equality—where we can bring together the best understandings and tools at our disposal for collective benefit––and help to rectify fiercely uneven power relations. Canada has an obligation to protect salmon populations and to support Indigenous food fisheries, especially in light of poorer marine conditions and therefore reduced salmon survival linked to climate change. As fish populations decline and thus become more valuable, greater commitment to conservation and FSC fisheries should occur.

Our approach in this study was *adaptive*, centering on how we reduce harm in salmon within the confines of the present management system and using the best tools at our disposal, stemming from both Western and Indigenous fisheries sciences. However, it may well be a *transformative* process that is required to contend with the increasingly complex set of pressures facing wild salmon today and in future. It is in fact only over the last century and a half that the shift away from Indigenous-governed fisheries has taken place, and it may well be the same scale of transformation, a reversion from productionist to regenerative thinking, that will be required in order to restore a healthy relationship between people and salmon. Not only would such a shift help in restorative salmon efforts––possibly precluding the need for studies such as this one if terminal known-stock fisheries were the future and incidental capture and release a thing of the past—but it would importantly help return power into the hands of Indigenous communities who are the longest-standing stewards of salmon. Rebuilding relationships in ways that respect and uphold Indigenous fishing rights and sovereignty is a critical step towards effective co-management, giving us greater collective ability to monitor and harvest productive salmon populations while protecting endangered ones.

4.8 Figures

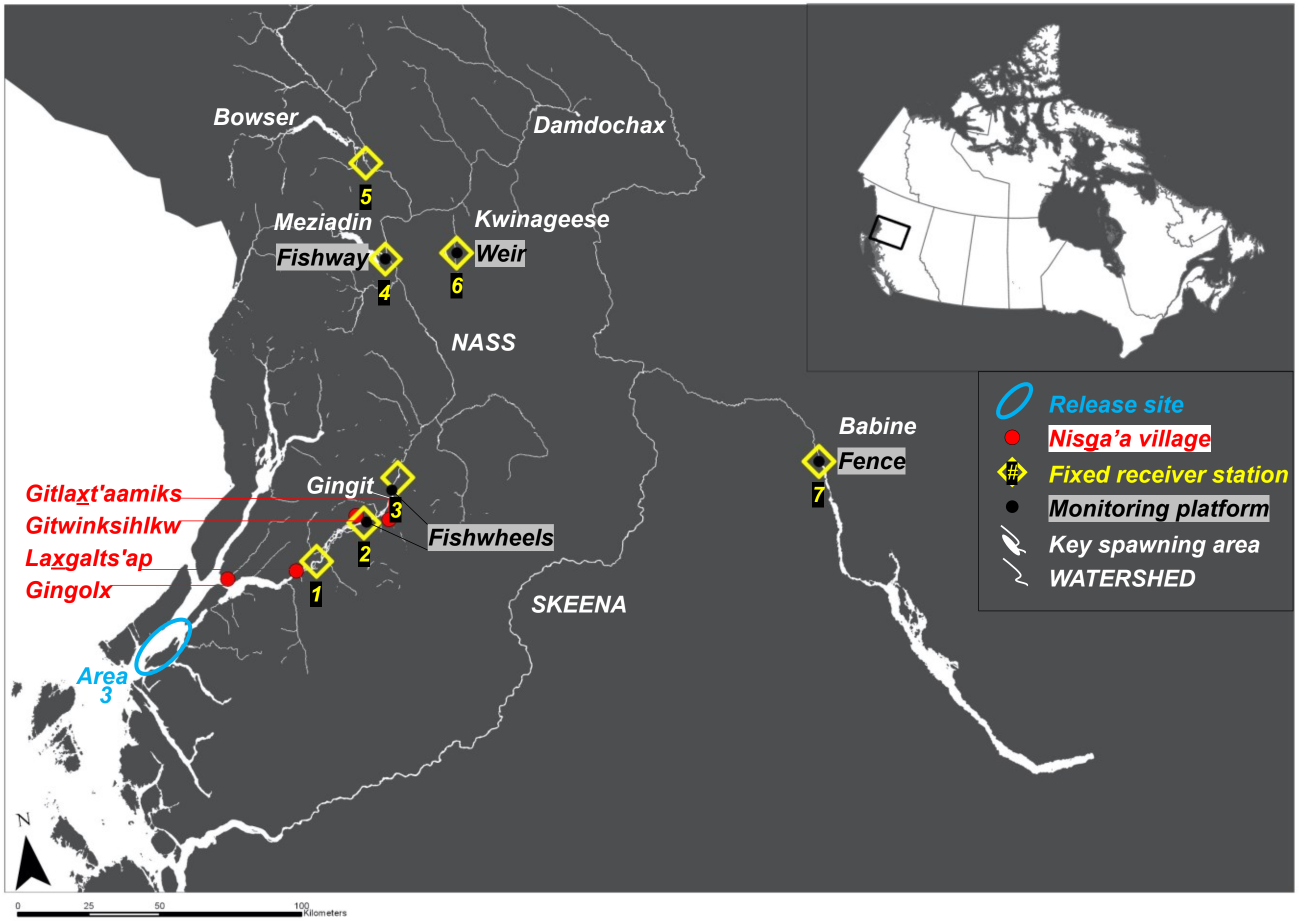


Figure 4-1 Map of Nass and Skeena watersheds and main spawning areas. Shown are the positions of Nisga'a communities (red circles; Nisga'a names shown in red), in-river monitoring platforms (black circles with descriptor), and stationary telemetry receivers (numbered yellow diamonds; see Table 4-3 for station details).

Geospatial data used to create this map are from the British Columbia Freshwater Atlas (Ministry of Forests, Lands, and Natural Resource Operations 2011) and the Nisga'a Fisheries and Wildlife Department.

Figure 4-2 Nisga'a fishwheel on Nass River, showing the location of the baskets, holding pen and trough, as well as current direction.
Photo credit: Nicole Morven, Nisga'a Fisheries and Wildlife Department Harvest Monitor Coordinator.

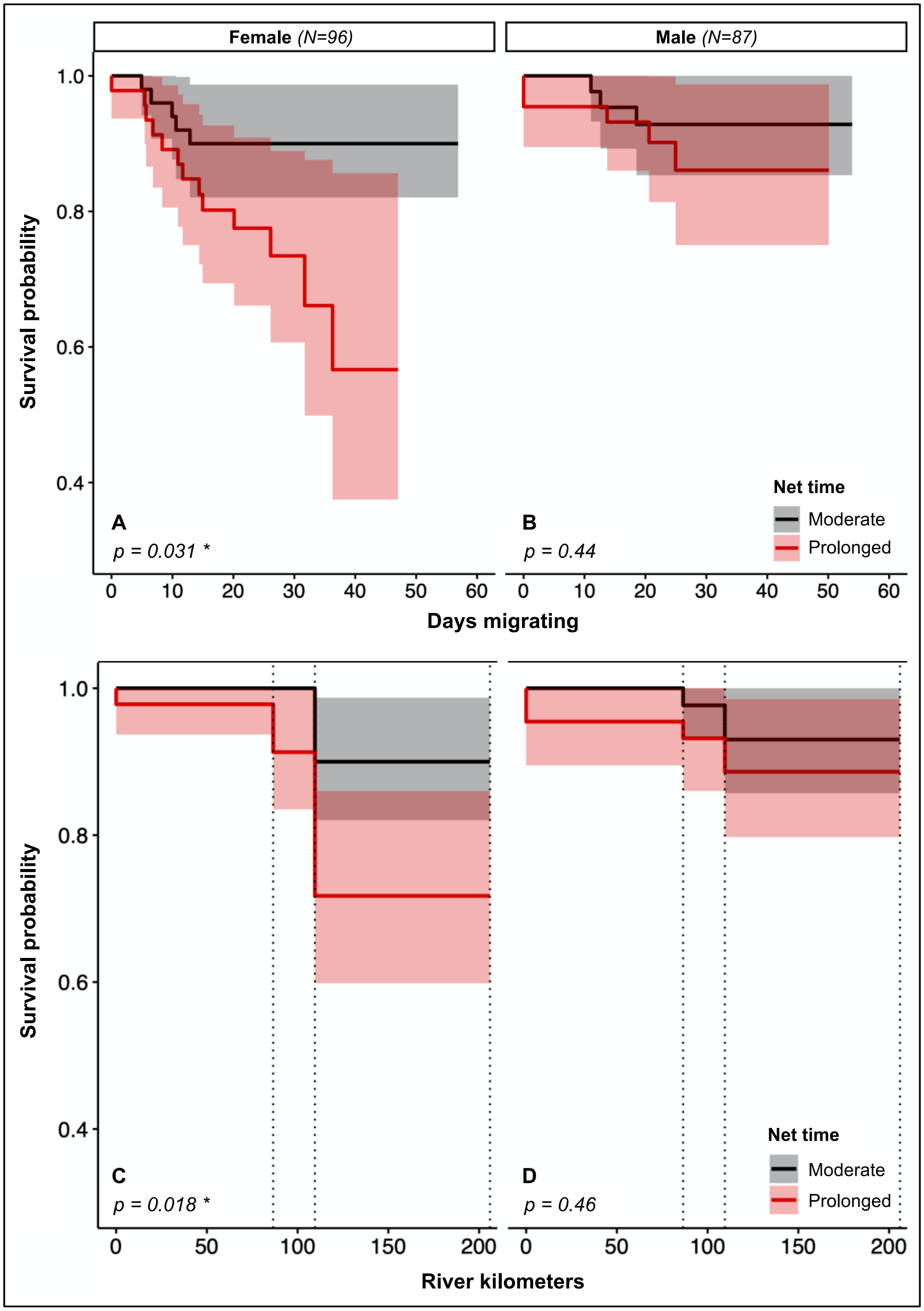


Figure 4-3 Meziadin sockeye salmon survival curves for net time groups (black = moderate; red = prolonged), facetted by sex (sample sizes shown), and displayed over days migrating (top) and distance in river kilometers (bottom; dotted vertical lines indicate positions of receiver stations where losses were observed).

Significance shown based on log–rank tests comparing survival curves; a single asterisk indicating significance at $p < 0.05$. Plots and 95% confidence intervals generated using the ggsurvplot() [in *survminer*] function in R.

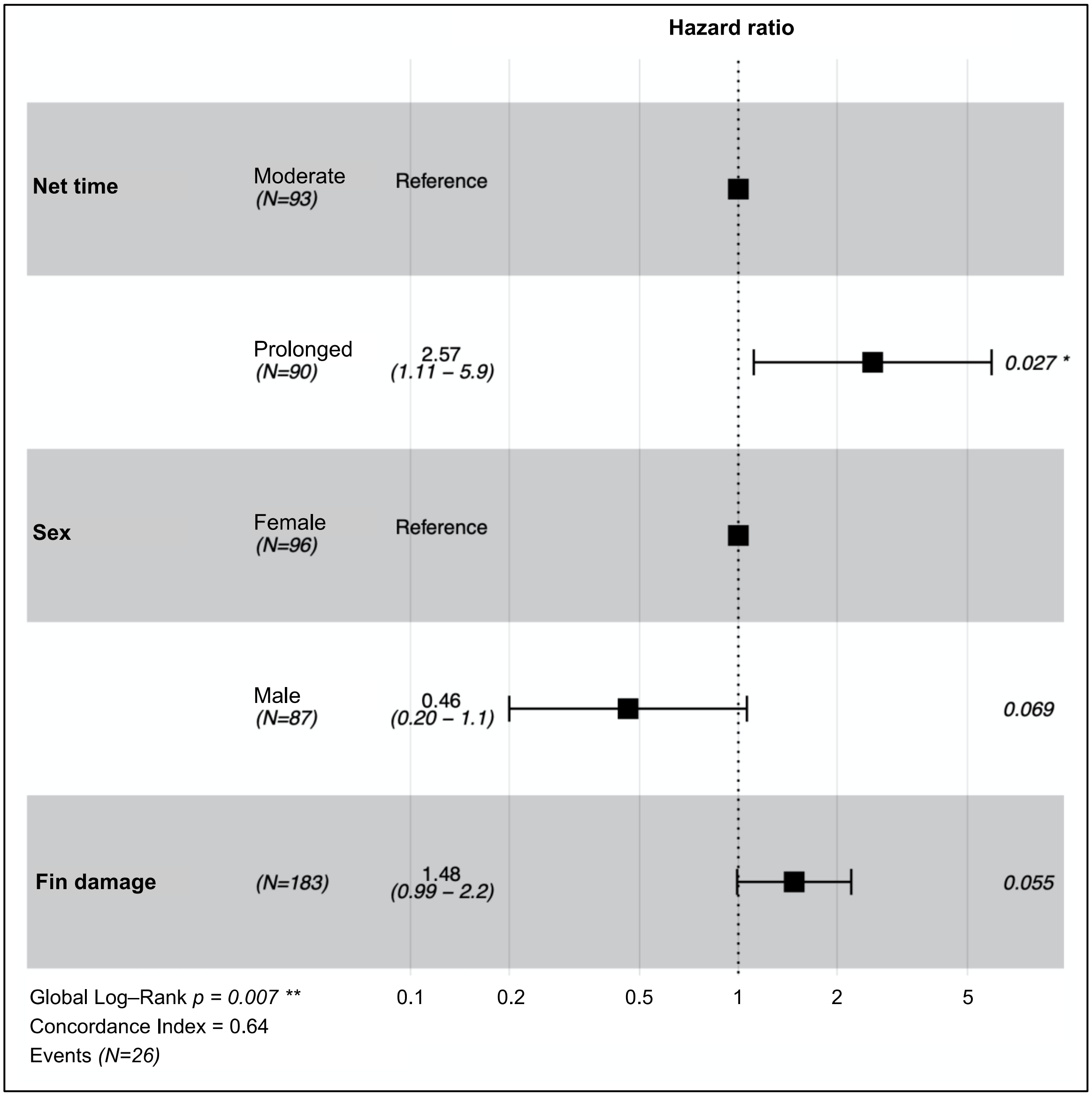


Figure 4-4 A graphical summary (forest plot) of the top Cox proportional hazards regression model (determined by AICc rank; see Table 4-6) of Meziadin sockeye salmon survival, including net time, sex, and fin damage as covariates.

Significance shown from log–rank tests by covariate and for the global model; a single asterisk indicating significance at $p < 0.05$ and two asterisks indicating significance at $p < 0.01$. Hazard ratios and 95% confidence intervals generated using the ggforest() [in *survminer*] function in R.

4.9 Tables

Table 4-1 Sockeye salmon harvest (retention) and release (bycatch) from the selective commercial purse seine fishery in Area 3, 2011–2019. Data source: Fisheries and Oceans Canada, Prince Rupert.

Year	Sockeye harvest (N)	Sockeye release (N)	Sockeye release (%)
2011	60,422	2,818	4.46
2012	5,366	2,359	30.54
2013	6,927	20,679	74.91
2014	20,885	16,941	44.79
2015	20,049	5,641	21.96
2016	495	46,174	98.94
2017	0	20,117	100.00
2018	159	3,941	96.12
2019	525	564	51.79

Table 4-2 Summary information for sockeye salmon (*N=395*) captured in a simulated commercial purse seine fishery in Area 3 in 2016.

Fish were held in the submerged pursed net for either a moderate (<15 min) or prolonged (30–45 min) amount of time prior to brailing to simulate sorting times characteristic of small and large sets, respectively, during normal fishery operations. Sex was determined from secondary sexual characteristics. Means and standard deviations are shown for fork length, fin damage, injury score, as well as reflex action mortality predictor (RAMP) score (from 0 = all reflexes present to 1 = all reflexes absent; reflexes tested included: tail grab (*does the fish exhibit:* a burst swim response?), body flex (response to restraint?), head complex (regular ventilation patterns?); vestibular-ocular response (eye tracking?), and orientation (equilibrium maintenance?). See Raby et al., 2012 for full details and approach validation.

N	**Net time**	**Sex**	**Fork length** (cm)	**Fin damage** (0–7)	**Injury** (0–3)	**RAMP** (0–1)
103	Moderate	Female	57.57±3.40	0.68±1.04	1.13±0.43	0.20±0.24
100	Moderate	Male	60.71±4.54	0.54±0.91	1.08±0.58	0.21±0.30
Overall means for moderate net time:				***0.61±0.98***	***1.10±0.51***	***0.20±0.27***
95	Prolonged	Female	58.09±3.31	0.84±0.95	1.27±0.59	0.22±0.29
97	Prolonged	Male	60.61±3.55	0.79±1.07	1.07±0.56	0.19±0.25
Overall means for prolonged net time:				***0.82±1.01***	***1.17±0.58***	***0.21±0.27***

Table 4-3 Receiver stations used to detect migrating tagged sockeye in the Nass (Stations 1–6) and Skeena (Station 7) Watersheds.

Shown here are approximate distances from the release site (Area 3; river km), location names, notable features, as well as station detection efficiencies [DE; the proportion of known tag transmissions that are detected by a given receiver: observed (Obs.) / expected (Exp.)]. Asterisks indicate station locations on Nass River mainstem; otherwise station names match the corresponding river.

Station	River km	Location	Feature	Obs.	Exp.	DE
1	61.00	*Laxgalts'ap	End of tidal zone	198	297	66.7%
2	86.50	*Gitwinksihlkw	Fishwheels	284	288	98.6%
3	109.50	*Grease Harbour	Fishwheels	267	267	100%
4	206.00	Meziadin	Fishway	156	157	99.4%[T]
5	260.00	Bell-Irving	Confluence	7	-	-
6	265.50	Kwinageese	Weir	21	21	100%[T]
7	495.50	Babine	Counting fence	23	26	88.5%[T]

[T]Estimates based on mobile tracking and/or physical recaptures of tagged sockeye at or upstream of these terminal stations (none performed for Bell-Irving, hence no DE).

Table 4-4 Summary information on the location, timing, and method(s) of opportunistic mobile tracking efforts throughout the Nass and Skeena Watersheds in August and September 2016.

Locations	Dates (2016)	Method(s)	By
Nass mainstem to Damdochax	Aug. 31	Helicopter	NFWD
Meziadin (downstream of Fishway)	Aug. 27; Sep. 8	Walk	AJR
Hanna-Tintina (upstream of Fishway)	Aug. 23/29; Sep. 5	Truck, walk	AJR
Fulton River Spawning Channel (upstream of Fence)	Aug 19/30; Sep. 6/16	Truck, walk	AJR
Pinkut Creek Spawning Channel (upstream of Fence)	Aug 19; Sep. 6	Truck, walk	AJR

Table 4-5 Fate outcomes for tagged sockeye by conservation unit (CU; sample sizes shown). Fate groups include: ocean mortalities (OM = never confirmed in natal river); river mortalities (RM = confirmed in natal river but not in natal spawning area); migration survivors (MS = confirmed in natal river and in natal spawning area); and fisheries removals (FR = reported removals by fishers, or tags detected in communities during permitted village scans). Natal areas were determined through confirmation on or near spawning grounds, or, when not found in spawning areas, through GSI analyses. For areas where no tracking took place (*i.e.,* most of the Skeena and all other watersheds), the fate outcomes of tagged sockeye could not be reliably distinguished and so are shown as a single combined value (based on GSI results).

<table>
<tr><th>Area</th><th>Sockeye CU</th><th>OM</th><th>RM</th><th>MS</th><th>FR</th><th>Total</th></tr>
<tr><td colspan="7">NASS</td></tr>
<tr><td>Lower</td><td>Gingit</td><td>0</td><td>0</td><td>2</td><td>0</td><td>2</td></tr>
<tr><td>Upper</td><td>Meziadin</td><td>3</td><td>23</td><td>157</td><td>23</td><td>206</td></tr>
<tr><td>Upper</td><td>Bowser</td><td>0</td><td>6</td><td>7</td><td>0</td><td>13</td></tr>
<tr><td>Upper</td><td>Kwinageese</td><td>5</td><td>10</td><td>21</td><td>0</td><td>36</td></tr>
<tr><td>Upper</td><td>Damdochax⊤</td><td>2</td><td>≤5</td><td>≥5</td><td>1</td><td>13</td></tr>
<tr><td>Unknown</td><td>Unknown⊥</td><td>0</td><td colspan="2">10</td><td>18</td><td>28</td></tr>
<tr><td colspan="2">Total</td><td>10</td><td>max. 54</td><td>min.192</td><td>42</td><td>298</td></tr>
<tr><td colspan="7">SKEENA</td></tr>
<tr><td>Lower</td><td>Alastair</td><td colspan="3">3 [1 → Nass]</td><td>0</td><td>3</td></tr>
<tr><td>Upper</td><td>Damshilqwit</td><td colspan="3">1</td><td>0</td><td>1</td></tr>
<tr><td>Upper</td><td>Sustut</td><td colspan="3">1</td><td>0</td><td>1</td></tr>
<tr><td>Upper</td><td>Halliday Slough</td><td colspan="3">11 [8 → Nass]</td><td>1</td><td>12</td></tr>
<tr><td>Upper</td><td>Babine</td><td colspan="2">26 [11 → Nass]</td><td>26</td><td>2</td><td>54</td></tr>
<tr><td colspan="2">Total</td><td colspan="3">68</td><td>3</td><td>71</td></tr>
<tr><td colspan="7">OTHER</td></tr>
<tr><td>Central Coast</td><td>Kitimat</td><td colspan="3">1</td><td>0</td><td>1</td></tr>
<tr><td>Central Coast</td><td>Kitlope</td><td colspan="3">3</td><td>1</td><td>4</td></tr>
<tr><td>Central Coast</td><td>Lowe</td><td colspan="3">1</td><td>0</td><td>1</td></tr>
<tr><td>Central Coast</td><td>Neechanz</td><td colspan="3">5</td><td>0</td><td>5</td></tr>
<tr><td>Stikine</td><td>Scud</td><td colspan="3">4</td><td>0</td><td>4</td></tr>
<tr><td>Unknown</td><td>Unknown⊥</td><td colspan="3">0</td><td>11</td><td>11</td></tr>
<tr><td colspan="2">Total</td><td colspan="3">14</td><td>12</td><td>26</td></tr>
<tr><td colspan="2">Grand Total</td><td colspan="3">338</td><td>57</td><td>395</td></tr>
</table>

⊤No stationary telemetry receiver. Helicopter surveyed (Aug. 31; **Table 4-4**), with 5 individuals detected on spawning grounds. Another 5 Sockeye were determined to be of Damdochax origin (from GSI), and all 5 passed all telemetry receivers downstream from this location. The fates of these fish cannot be reliably assessed, hence the uncertainty indicated for RM and MS.

⊥GSI analyses either failed or were not performed for these fish. For those in the Nass watershed not removed by fisheries (*N=10*), all were detected in-river and none were confirmed in monitored spawning areas, however, some may have survived to unmonitored, smaller spawning areas in the Lower Nass River (*e.g.*, Gingit) so whether RM or MS cannot be assessed.

Table 4-6 Top five models (determined by AICc rank) of survival over time for Meziadin sockeye salmon fitting Cox proportional hazards regression (Coxph) models.

Model structure	df	AICc	ΔAICc	Weight
net time + sex + fin damage	3	252.66	0.00	0.11
net time + sex	2	253.30	0.63	0.08
net time + fin damage	2	253.66	1.00	0.07
net time	1	254.75	2.09	0.04
net time + sex + fin damage + fork length	4	255.04	2.38	0.03

Chapter 5: Survival of sockeye salmon following gillnet escape – in search of sustainable fisheries solutions

5.1 Abstract

1) Abundant and sustainable Pacific salmon (*Oncorhynchus* spp.) stocks are foundational to cultures, ecosystems, and economies throughout the North Pacific, but their future is increasingly uncertain as climate change and other anthropogenic forces transform their migratory path. Gillnets, a dominant fishing gear used in some locales, have low retention rates, resulting in 'escapees' who are often wounded and whose chance of survival is likely reduced as waters warm. In the Fraser River of British Columbia, a remarkable number of sockeye salmon (*O. nerka*) arrive on spawning grounds with injuries consistent with having struggled free from a gillnet, yet experimental studies are lacking that examine sockeye gillnet escape and its impact on survival.
2) Here, we tested the hypothesis that gillnet related injury, when coupled with peak river temperatures, would trigger high levels of mortality. We also tested how the magnitude of escape mortality varied with how gillnets were strung: loosely versus tightly. We simulated escape for adult summer-run sockeye salmon in the Lower Fraser River and used biotelemetry to assess survival.
3) Gillnet escapees experienced 28% higher migration mortality than controls. Time-to-event analysis revealed that the top predictors of survival were injury, temperature, and treatment. Migration mortality risk was increased between two- and three-fold for fish with severe injuries, that were captured in waters >19ºC, and who experienced escape from a tight gillnet. Across major stocks, experiencing escape reduced sockeye survival

for Chilko (by 25%), Stuart (37.5%), and Stellako (53%), in alignment with expectations of greater climate change resilience among Chilko sockeye.

4) Survival following gillnet escape could be promoted if fisheries took place when more climate change resilient populations are running, during cooler periods, and/or with gears that reduce entanglement impacts, such as more loosely strung gillnets. Other alternative solutions (*e.g.*, gear modifications, transitioning to new or traditional gears) warrant investigation.

5.2 Introduction

Abundant and sustainable Pacific salmon (*Oncorhynchus* spp.) stocks are foundational to diverse cultures (Brooks et al. 2012), ecological systems (Naiman et al. 2002), and economies (Pacific Salmon Foundation 2014) throughout the North Pacific, but they face an increasingly uncertain future as climate change and other anthropogenic stressors transform their migratory path. Most Pacific salmon are now encountering warmer water conditions, both in ocean and fresh waters, as they complete their spawning migration. Now warmer than at any other time since written records were kept, British Columbia's Fraser River has seen a progressive ~2°C rise in peak summer river temperature in the last half century, with climate models predicting another 2-4°C increase in the decades ahead (Martins et al. 2011). High migration mortality has been attributed to these elevated temperatures, especially for sockeye salmon (*O. nerka*) who have suffered severe declines (an estimated 5-10 million, 1990-2010; Hinch and Martins 2011) with wide-reaching impacts as both an ecological and cultural keystone species (Garibaldi & Turner 2004).

Gillnets, a dominant gear type used in both the commercial fishing industry and Indigenous fisheries, have been shown to have low retention rates (Chopin & Arimoto 1995), resulting in 'escapees' (*i.e.,* fish that escape from nets) who are often wounded and whose chance of survival is likely reduced as waters warm. In the Fraser River, a staggering number of sockeye that are assessed on spawning grounds suffer skin damage consistent with having struggled free from a net: 10-40% in 1987-1994 (Clarke et al. 1994) and 19-27% in 2014-2016 (Bass et al. 2018a), with a daily prevalence of gillnet-injured sockeye ranging from 0 to 80% of individuals assessed. A predictive relationship has since been established between the proportion of sockeye spawners with gillnet injuries and the extent of fishing effort (Kanigan et al. 2019), with mounting evidence that considerable numbers of gillnet-injured females fail to reproduce on spawning grounds (Baker & Schindler 2009; Bass et al. 2018a). The high temperatures now encountered during spawning migrations leave sockeye with little aerobic scope (Eliason et al. 2011), and thus less able to cope with high flows, predators, and/or escape, meaning potentially serious, population-level consequences from the co-occurrence of escape and high river temperatures.

Recent studies have examined how net capture and release impact sockeye survival to natal areas (Donaldson et al. 2011; Nguyen et al. 2014), and some have in fact studied sockeye escape in laboratory settings (Thompson & Hunter 1971; Teffer et al. 2017), but experimental studies are lacking that examine sockeye escape from fishing gear in the natural environment where conditions are changing rapidly. A critical distinction between the study of release and escape relates to the extent of air exposure, where the release of salmon typically involves physical handling to remove the fish from the net by hand, often exposing fish to air for a minute or more (Cook et al. 2015), whereas escape takes place entirely underwater. A minute of air exposure causes both immediate and long-term impairment in sockeye, with increased rates of delayed mortality found in laboratory studies (Gale et al. 2014). While escape has been linked to injury and stress in sockeye which can lead to disease development and immediate or delayed mortality (Teffer et al. 2017; Bass et al. 2018a), this has never been directly assessed in the wild making it difficult to predict interactive effects of fishing approach, escape related injury, and warming temperatures on migration and spawning success (Raby et al. 2015a). The scale of fisheries related injury in Fraser sockeye, and thus the potential for immediate or delayed mortality (Patterson et al. 2017), may be substantial as sockeye appear to routinely escape from fishing gear and in increasingly warm waters.

Our objective here was to conduct rigorous experimentation to test hypotheses concerning the effects of injury and high temperature on migration mortality and spawning success in Fraser River sockeye salmon following escape from gillnet fisheries. We hypothesized that injury associated with gillnet escape, when coupled with peak summer river temperatures, would precipitate high levels of immediate and delayed mortality and impact spawning success. We also anticipated that the magnitude of escape mortality would vary with how gillnets were strung, specifically testing those strung loosely versus tightly which is reflective of different net designs used in the fishery. Our ultimate aim with this work is to provide fisheries managers, rights holders, and stakeholders (including commercial fishers) with knowledge to guide future adaptation strategies given a clear need for approaches and tools to adapt to climate change and ensure salmon stocks are harvested with conservation and long-term sustainability as key priorities. The critical importance of healthy, wild Pacific salmon populations for the social-ecological systems they underpin cannot be overstated, and the increasing precariousness of their populations gives urgency to the need for sustainable fisheries solutions.

5.3 Methods

We focus this study on homing adult summer-run sockeye salmon which, in some years, constitute the largest run timing group in the Fraser River (~2-3 million per year; Hinch and Martins 2011) and are comprised of a few major stocks (*e.g.*, Chilko, Stuart, Stellako, Quesnel) and several smaller ones. In the Lower Fraser River, on the territory of the Peters First Nation (**Figure 5-1**), we worked with Stó:lō fishers between August 8 and 22, 2017 to capture sockeye by 'scientific' beach seine (*i.e.,* not part of the commercial or Indigenous fishery; under scientific research permit XR 208 2017) where fish were corralled and individually dip-netted out of deep flowing water and placed in flow-through pens prior to undergoing experimental procedures. Over this timeframe, mean daily water temperatures ranged from 18.1ºC to 20.0ºC during the peak temperature period (**Figure 5-2**).

Sockeye (*N=385*) were divided into four approximately equal groups: two control (1 non-biopsied and high-graded; 1 biopsied and not high-graded), and two escape (1 min entanglement reflecting 'loose gillnet'; 1 min entanglement reflecting 'tight gillnet'; **Figure 5-3**). To expose the latter two groups to simulated escape events, we forced entanglement and liberation from a monofilament commercial gillnet (13.3 cm mesh). All fish were then immediately placed into a flow-through trough for various assessments and sampling. First, sex was determined from secondary sexual characteristics and fork length (FL) was measured (minimum 45 cm; otherwise released). Second, injury level and rapid indicators of behavioural impairment (specifically, reflex action mortality predictors 'RAMP'; Davis 2010) were assessed following established procedures (**Table 5-1**). Finally, for all fish except for the non-biopsied control group, two small biopsies (1 operculum punch; 2-3 gill filament tips) were taken to assess genetic stock identification (via DNA analysis following Beacham et al. 2004) and pathogen load (for a separate study; data not presented herein).

Prior to release, a coded radio transmitter (Pisces 5, 43 mm length x 16 mm diameter, 15.2 g in air; Sigma Eight Inc., Newmarket, ON) was gastrically implanted in each sockeye, and an external numbered anchor tag (FD-94; Floy Tag & Mfg. Inc., Seattle, WA) was inserted into the dorsal musculature for individual identification. Total handling time was on average 1.9 min per fish (range: 1-3 min). This specific method combination and sequence was pioneered by members of our research team (Cooke et al. 2005), and all practices followed approved animal care protocols from the University of British Columbia. To every extent possible fish air exposure was avoided, totalling < 10 sec to transfer fish between the flow-through pen, trough, and back to the river.

To monitor fish passage upstream and assess survival outcomes, fixed telemetry arrays were set up along the Fraser River and at spawning areas (up to ~800 river km from the site of release; **Figure 5-1A**). The placement of receiver stations (Orion receivers [Sigma Eight Inc., Newmarket, ON] equipped with 3- or 4-element Yagi antennas) required permission and site access from multiple First Nations, private landowners, and provincial and federal agencies. Mobile tracking was also performed at spawning areas (**Figure 5-1A**; additional details in **Table 5-2**), and with efforts from federal stock assessment personnel monitoring major spawning areas, the extent to which females failed to reproduce was assessed based on the percentage of eggs retained after death. From information listed on tags, as well as posters placed in key areas in the watershed, fishers could report the location and details of any sockeye captured and be entered in a reward lottery.

Tracking continued until the end of the Fraser sockeye migratory period (mid-October). Radio detections were filtered so that those separated by less than three seconds (the burst rate of radio tags) or more than 30 seconds (likely false positives) were removed. An estimated migration path was then built for each sockeye, where detection, recovery, and fisheries capture histories were brought together and plotted over river distance so that information could be cross-validated, and spurious detections could be inspected and potentially removed. These data were used to calculate detection efficiencies for each station (presented in **Table 5-3**), and to then assess sockeye survival outcomes: (1) immediate mortality = not detected ascending river from release site; (2) delayed mortality = detected ascending river from release site but not entering natal area; (3) migration survival = detected entering natal area; and (4) fisheries removal = reported by fishers. Natal area was determined from DNA analysis (except for non-biopsied controls who were assigned to the spawning area they entered (if applicable) or otherwise remained of unknown stock and fate and were therefore excluded from subsequent survival analyses).

5.3.1 Statistical Analyses

All analyses were performed using the R statistical software, version 3.6.3 (R Core Team 2017). With treatment, injury level, and survival outcome all being categorical data, Pearson's chi-squared tests for count data were conducted to inspect between-group associations and correlation matrices were visualized from Pearson residuals using the R package *corrplot* (Friendly 2002). As RAMP is an ordinal variable, Kruskal-Wallis rank sum tests were performed to compare scores across treatment, injury level, and survival outcome groups.

Time-to-event analysis, specifically Cox proportional hazards regression (Cox 1972), was used to examine the association between survival across migration and multiple predictor variables: treatment; sex; FL; injury level; RAMP; and water temperature. In two separate model iterations, water temperature was included first as a continuous covariate, and then second, categorically based on an important potential physiological tipping point (19ºC; Martins et al. 2011). A global model was fit using the 'coxph' function in the *survival* package and plotted using *survminer* (Kassambara et al. 2017). The model was right-censored (status: 1=mortality; 0=survival), with fisheries removals being censored at their point of fisheries capture. The 'dredge' function in the R package *MuMIn* was used to compare all possible covariate combinations and ranked them based on Akaike's information criterion corrected for small sample sizes (AICc; Akaike 1974; Burnham and Anderson 2002). The best fit model was considered that with the lowest AICc value, and it was used to estimate model coefficients. Models with ΔAICc < 2 were considered competing models, and models were validated to verify that underlying statistical assumptions were not violated (Cox 1972).

Power analysis was performed to investigate our ability to compare survival curves within sockeye populations using the 'ssizeCT' function in the *powerSurvEpi* package (where power=0.8; α=0.05; k=1; Qiu et al. 2018), after which log-rank tests were used to compare survival curves.

5.4 Results

The sampling period of summer-run sockeye salmon in this study resulted in the capture of three major stocks (Chilko: 42%; Stuart: 22%; Stellako: 10%) and several small ones (**Figure 5-1B**). A total of 52 sockeye were classified as immediately mortalities (13.5%), 126 as delayed mortalities (32.7%), 175 as migration survivors (45.5%), 20 as fisheries removals (5.2%), and 12 unknowns (3.1%). Experiencing immediate or delayed mortality was found to be 28% higher for escapees than for control fish. Survival outcome varied significantly by treatment ($X^2 = 35.64$, $p < 0.001$), where escapees were positively correlated with immediate mortality (and to a lesser extent, delayed mortality and fisheries removal), and controls were positively correlated with migration survival (**Figure 5-4A**). Survival outcome also varied significantly by injury level ($X^2 = 31.43$, $p < 0.001$). Moderate and severe injuries were positively correlated with immediate mortality and fisheries removal, whereas minor injuries were positively associated with migration survival and delayed mortality (**Figure 5-4B**). Injury level also varied significantly with treatment ($X^2 = 46.46$, $p < 0.001$), where minor injuries were positively correlated with non-biopsied control fish (as would be expected based on high-grading), while moderate and severe injuries were more associated with escape groups (**Figure 5-4C**). RAMP score differed significantly only by injury level ($p = 0.015$; all other comparisons $p > 0.2$).

Three competing survival models were identified (**Table 5-4**). Treatment, injury level, and water temperature at tagging were in each top model, with RAMP included in only the second ($\beta = 0.67$, 95% C.I. = -0.34 – 1.69), and FL included in only the third ($\beta = -0.02$, 95% C.I. = -0.08 – 0.04). Based on the best fit model, a significantly higher hazard (or mortality risk) was found for fish: with severe injuries ($\beta = 1.13$, 95% C.I. = 0.66 –

1.61; $h = 3.18$); captured in waters >19ºC ($\beta = 0.64$, 95% C.I. = 0.29 – 1.00; $h = 1.90$); and from the tight gillnet treatment group ($\beta = 0.58$, 95% C.I. = 0.19 – 0.97; $h = 1.80$; **Figure 5-5**). A significantly lower risk was found only for sockeye from the non-biosied control group ($\beta = -0.72$, 95% C.I. = -1.29 – -0.15; $h = 0.49$). Water temperature was a highly significant predictor ($p < 0.001$) whether it was included as a categorical or continuous covariate (**Table 5-4**), with no meaningful differences in competing model outcomes in either scenario, but with lower AICc and higher model weight associated with its inclusion in categorical form.

Three sockeye populations had adequate sample sizes ($N \geq 32$) to inspect for survival curve differences. Across Chilko, Stuart, and Stellako, survival curves for escapees were consistently and significantly lower than for controls ($p < 0.05$, although only near-significant in the case of Chilko at >19ºC), with mortality rates higher for each group under warm water conditions (>19ºC; **Figure 5-6**). Using controls as a baseline for comparison, we find that experiencing escape reduced sockeye survival for Chilko by 25%, Stuart by 37.5%, and Stellako by 53%. Few sockeye were recovered in major spawning areas (3 males [1 escapee]; 8 females [4 escapees]), with all females having spawned 100%, save for one female (an escapee; spawned 0%). Finally, apparent straying behaviour was minimal (~5% across Chilko, Stuart, and Stellako) except for in Harrison Lake where nine of 15 sockeye detected here via mobile tracking belonged elsewhere based on DNA results. Four of these fish were detected first ascending the Fraser River from the release site but then showed downstream movement (*i.e.,* fallback) to Harrison Lake. Eight were escapees, and all were initially captured in >19ºC waters.

5.5 Discussion

This study is the first to experimentally examine in the field interactive effects of fishing approach, escape related injury, and warming temperatures on the migration and spawning success of wild Pacific salmon. In line with our leading hypothesis, we found that injury associated with gillnet escape, when coupled with peak summer river temperatures, indeed triggered high levels of mortality across the return migration of homing adult sockeye salmon. However, based on a very limited sample size, we found minimal evidence to support our expectation (Baker et al. 2013; Bass et al. 2018a), of similar negative consequences for spawning success. Our second hypothesis, that the magnitude of escape mortality would vary with how gillnets are strung (loosely versus tightly), was substantiated by our findings with implications for adaptive management strategies moving forward (discussed below).

On the whole, we found that gillnet escapees experienced 28% higher immediate and delayed mortality than control fish. We also found positive correlations between experiencing escape and these adverse survival outcomes. Likewise, escapees tended to be more injury prone, and both moderate and severe injury were positively correlated with both immediate mortality as well as fisheries removal. This last finding, that suggests greater vulnerability to fisheries capture among escapees, could be due to their being in a more compromised condition with reduced capacity to evade fishers (similar to predation or disease; Chopin and Arimoto 1995). Similar factors could also come to explain the straying behaviour observed among sockeye tracked to Harrison Lake in this study, where almost all were escapees captured in >19ºC waters, given that environmental stressors have been suggested to influence the onset of this behaviour (McConnell 2017). Future work could explicitly test whether these combined stressors affect fisheries capture or straying.

Time-to-event analysis revealed that the top predictors of sockeye survival included injury level, water temperature, and treatment. Specifically, based on our best fit model, fish with severe injuries were found to be ~3x more likely to experience migration mortality than those with minor or moderate injuries. Likewise, fish initially captured in waters >19ºC faced nearly twice the mortality risk as those captured at <19ºC. Finally, we found that fish who experienced simulated escape involving a tight gillnet were nearly twice as likely to die before reaching natal areas than fish from the biopsied control and loose gillnet groups. Conversely, the risk was halved for fish belonging to the non-biopsied control group, in strong general alignment with previous lab-based research on gillnet-escaped sockeye which found large consequences for each additional level of handling or disturbance applied in salmon survival studies, such as biopsy sampling (Teffer et al. 2017). This finding may have also been driven, at least in part, by the high-grading practice for these fish where sockeye were selected to be in top condition (*i.e.,* uninjured, apparently healthy) to represent a best case scenario.

A large methodological challenge in this research and the interpretation and application of these results relates to the double capture event at the start of this study. Sockeye were captured first by beach seine before being treated and released from gillnets, likely causing these fish to experience higher levels of migration mortality than they would in a true escape scenario. As the same can be said for the control fish in this study, the comparative approach taken throughout (*i.e.,* using controls as a baseline for comparison) helps to address this issue in part. But the concern remains that mortality observed in survival studies of this nature, that involve double capture events, handling and sampling stress, as well as tag burden, are likely to overestimate the impacts of escape from fishing gear in the natural environment which would involve only some of these same stressors (*i.e.,* a single capture event, associated stress and injury).

Beyond the lack of observed influence of gillnet escape on spawning success (likely driven by the small sample size), another unexpected finding in this work is the notable absence of sex as a covariate in top survival models given the growing number of studies indicating greater female sensitivity to most perturbations (Hinch & Martins 2011b; Martins et al. 2012; Minke-Martin et al. 2018; Eliason et al. 2020). One possibility here is that the signal linked to sex-related effects may be overwhelmed when other stressors are severe and prolonged. It may be that the very high water temperatures encountered by sockeye in this study diminished observation of sex effects. Yet another consideration stems from the mesh size used in this study (13.3 cm) which is known to be selective for large sockeye (FL = 58-60 cm; Peterson 1954) which were predominantly male in this study (67%). Larger, and often deeper-bodied, fish may experience harsher gillnet entanglements and greater damage from escape, potentially putting them on par with females. Given variation in body shapes and sizes across stocks (Crossin et al. 2004), there may be potential here for population-level selection due to gillnet escape (Baker et al. 2011) that warrants further consideration and study.

Another potential driver of population-level selection stems from stock-specific differences in thermal tolerance (Martins et al. 2011), where some sockeye stocks (such as Chilko) are able to maintain cardiorespiratory performance at higher water temperatures—emerging as potential "superfish" under climate change scenarios—whereas others (such as

Stuart/Stellako) have demonstrably high physiological limitations in aerobic performance making them more susceptible to high temperature impacts (Eliason et al. 2011). In line with these findings, our survival analyses for the major stocks in this study indicate the lowest overall survival for Stuart and Stellako escapees at >19ºC, although reductions in survival are apparent across all three populations at elevated temperatures. This is perhaps an additional reason for conservation concern as Stuart and Stellako sockeye are already in a more vulnerable state ('Endangered' and 'Special concern', respectively) than their Chilko counterparts ('Not at risk'; COSEWIC 2017).

5.6 Management Implications

As noted by English et al. (2011) "While there is little that can be done about annual water temperatures or difficult passage points, it is possible to minimize cumulative environmental effects and fishery related factors by dissociating the timing and location of in-river fisheries from these other stressors." Based on our collective findings in this study, we consider the minimization in overlap between the integrated stressors studied here (gillnet escape, warming waters) to be a key consideration for management.

Adapting in-river gillnet fisheries so that they take place during cooler periods and/or when more climate change resilient populations are running could help minimize escape related mortality. The first option could take the form of limiting fisheries activities at times of the day or season when water temperatures rise above a particular threshold, but consideration must also be given to the tendency for salmon to seek cold water refugia during thermal peaks (Mathes et al. 2009), where they favour migrating at cooler periods so targeting them specifically at these times could have important impacts on their ability to evade fisheries capture and reach spawning grounds. The second option could be achieved through staggered fishery openings so that pulses of more vulnerable populations can navigate the river without interference (as also suggested by Kanigan et al. 2019). Current management models are adjusted for stock-specific mortality rates based on environmental conditions, including water temperature (Macdonald et al. 2010), but they do not yet account for mortality resulting from gillnet escape, or stock-specific responses to the integrated stressors studied here.

Beyond modifying *when* gillnet fishing occurs, there is also the question of *how*. Here we find that the physical conditions of entanglement and escape influence subsequent survival. There is an apparent survival advantage for sockeye that experience escape through a loose gillnet versus a tight gillnet. The former is comparable to temporary entanglement in tangle or trammel nets where fish become enwrapped around the body in netting, while the latter is reflective of a conventional gillnet where fish become entangled behind the operculum, which protects the sensitive gill organ. The picture becomes less clear when we examine injury level associated with each treatment, where we find more severe injury in connection with loose gillnets, and more moderate injury with tight gillnets. However, this may be explained by the way in which injury was assessed which focused on visible external injuries to the body. Gillnets of course disproportionately damage the gill structure which can have profound impacts on upstream survival, though this can be difficult to assess visually. The fact remains that simulated escape from a tight gillnet greatly increased the migration mortality risk for sockeye in this study, which could lend support for the use of alternative gears that promote corporal entanglement over operculum entanglement.

As global climate change and other anthropogenic forces continue to transform the aquatic environments that sockeye, other salmonids, and indeed many other organisms rely on, we will need creative and adaptive strategies that minimize the impact of these stressors and their interactions. Although we report potentially grave survival outcomes for sockeye who escape from gillnets in this study, we also identify specific contexts in which escape related mortality may be effectively reduced. Our results suggest that survival following gillnet escape could be promoted if fisheries took place during cooler time periods, when more climate change resilient populations are running, and/or with gears that reduce entanglement severity. The neighbouring Columbia River gillnet fishery has undergone tremendous transformation as of late, most recently implementing non-tribal gillnet bans (Morrow 2019), which could be the future in many other systems like the Fraser River if the impacts of potentially harmful fisheries practices cannot be reduced. Other solutions may be found through modifications to fishing gear (*e.g.*, different gillnet hang ratios, mesh sizes, and/or filament types), transitioning to new (or long-standing) approaches that could improve fisheries sustainability (*e.g.*, pound nets, fish traps; Tuohy 2018), and learning from past practices and Indigenous knowledge systems tied to traditional gillnets which were constructed from natural fibres and varied in form and function across locations and contexts (Stewart 2008), but which have been widely replaced by synthetic monofilament nets. Further investigating these possibilities and envisioning new paths forward will be an important area of research as we work towards building more sustainable and abundant salmon populations.

5.7 Figures

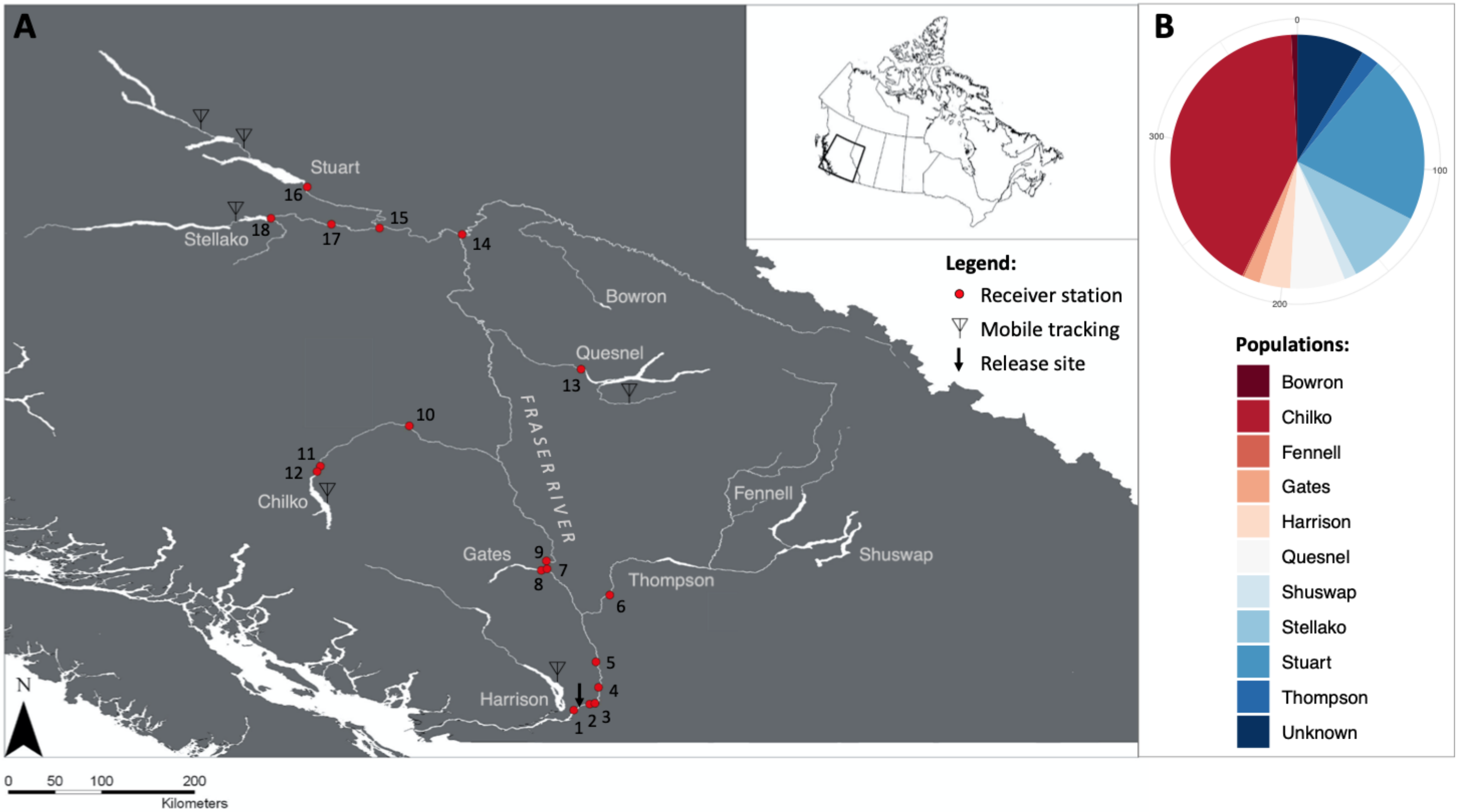


Figure 5-1 Map (A) and numerical proportions (B) of natal areas to which adult summer-run sockeye salmon belonged in the Fraser River of British Columbia in 2017.
Locations of receiver stations (red circles; *N=18*), mobile tracking sites (antenna; *N=6*), and the site of initial capture and release (black arrow) in the Lower Fraser River, on the territory of the Peters First Nation near Hope, BC. Geospatial data used to create (A) are from the British Columbia Freshwater Atlas (Ministry of Forests, Lands, and Natural Resource Operations 2011). An 'unknown' category is included in (B) for fish from the non-biopsied control group for which DNA analysis could not be performed and natal area could not be inferred from completing the migration.

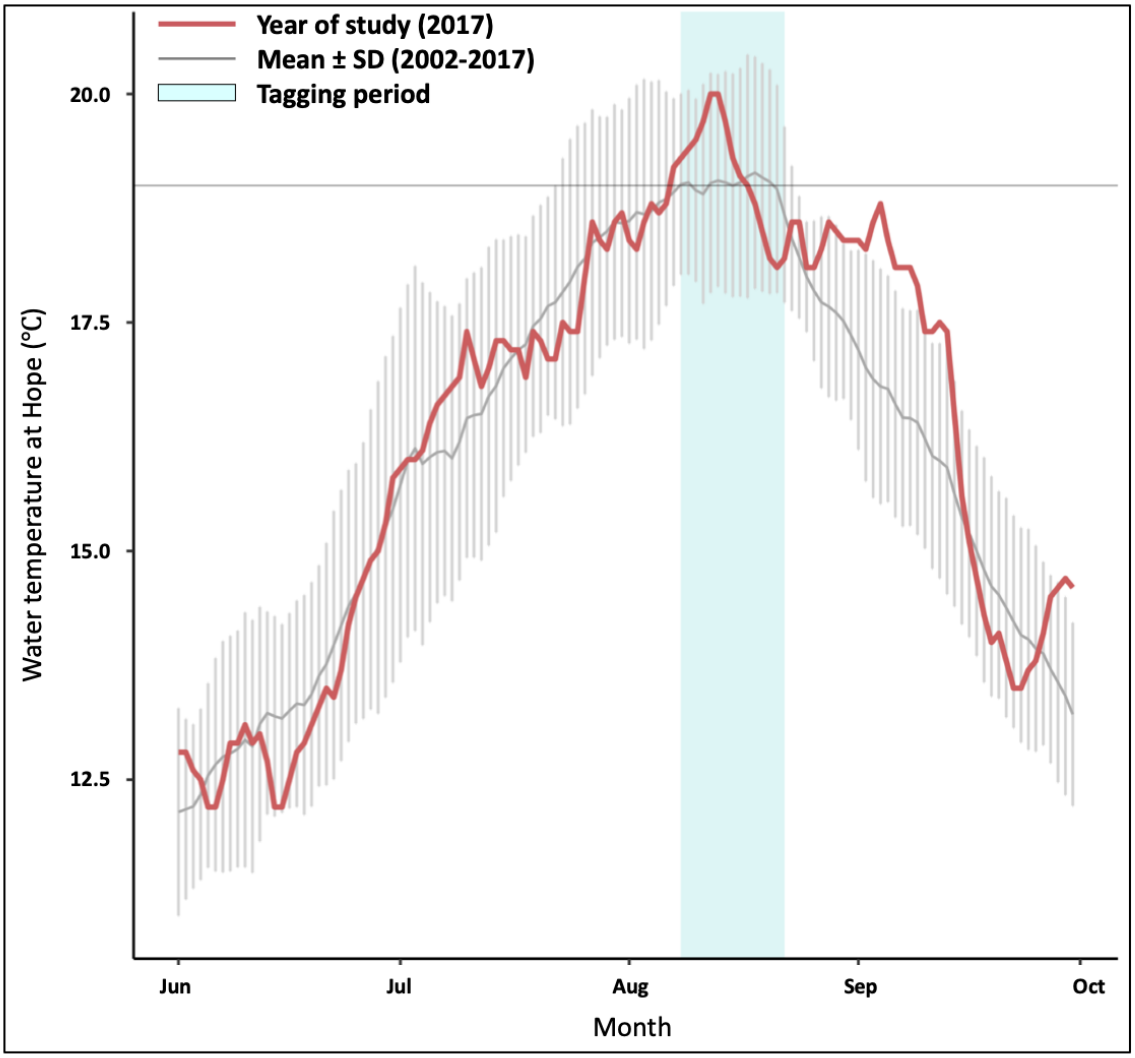


Figure 5-2 Fraser River water temperatures at Hope from June to October 2017, with the tagging and release period indicated by the blue rectangle.

19°C (where sockeye salmon begin to show early signs of physiological stress and elevated levels of mortality; Martins et al. 2011) is shown by the horizontal line. Data used to create this plot are provided by Fisheries and Oceans Canada's Environmental Watch (EWatch) team.

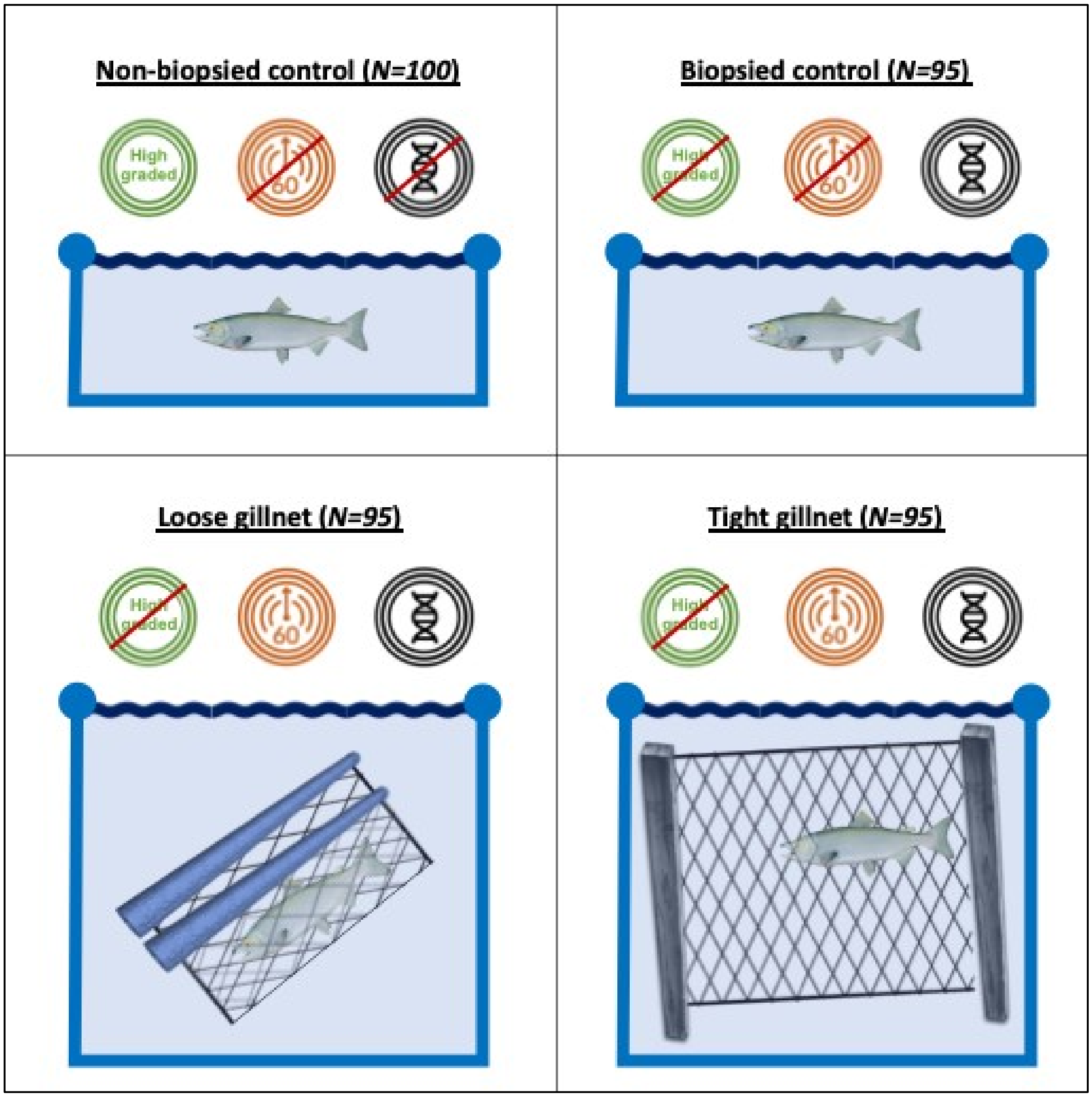


Figure 5-3 Experimental treatments for adult summer-run sockeye salmon in the Fraser River in 2017.
Sockeye (*N=385*) were divided into four approximately equal groups. TOP = two control: non-biopsied and biopsied. BOTTOM = two escape: loose and tight gillnet. Only non-biopsied controls were subject to high-grading (green symbol) and excluded from biopsy sampling for genetic stock identification (black symbol). Escape treatments involved up to a maximum of 60 sec forced entanglement (orange symbol) and liberation from a monofilament commercial gillnet (13.3 cm mesh).

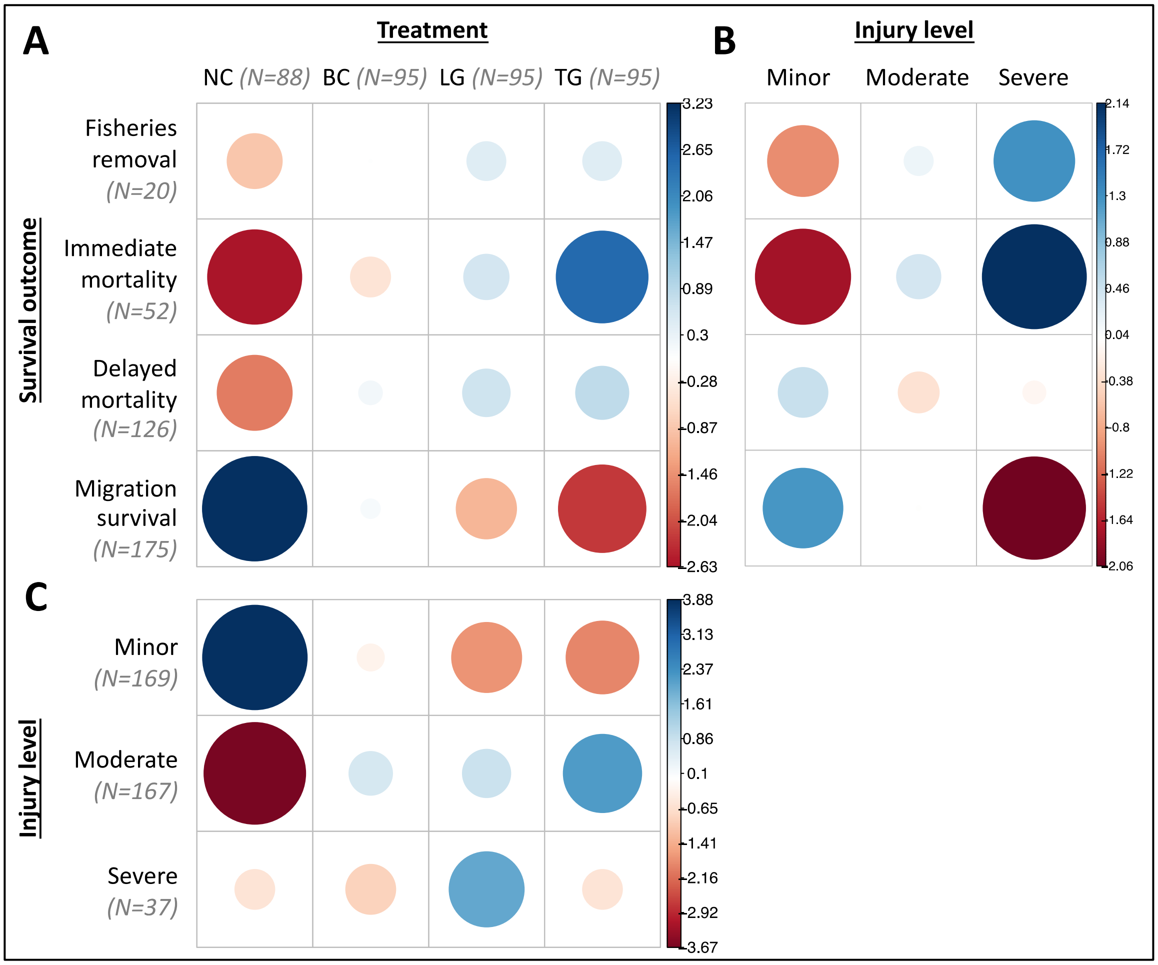


Figure 5-4 Correlation matrices visualizing Pearson residuals using the R package *corrplot* (Friendly 2002).
Residuals are from chi-squared tests for count data associating three groups of categorical data: treatment, injury level, and survival outcome. Treatment groups include non-biopsied control (NC), biopsied control (BC), loose gillnet (LG), and tight gillnet (TG). Sample sizes shown for each group.

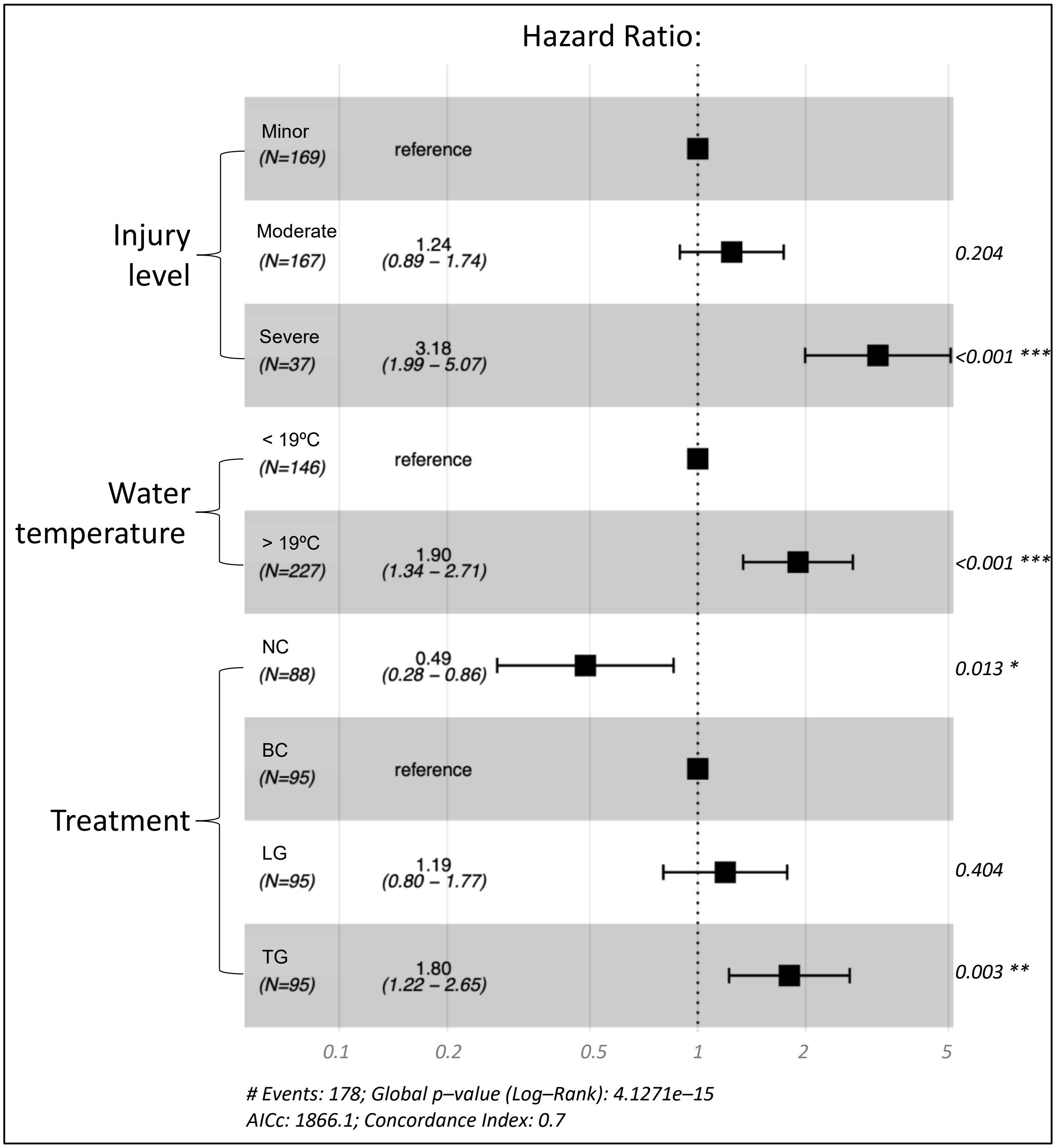


Figure 5-5 A graphical summary (forest plot) of the top Cox proportional hazards regression model (determined by AICc rank; see Table 5-4) predicting sockeye survival, including injury level, water temperature (at initial capture), and treatment as covariates.
Treatment groups include non-biopsied control (NC), biopsied control (BC), loose gillnet (LG), and tight gillnet (TG). Significance from log-rank tests and sample sizes shown for each factor and for the global model; significance shown at $p < 0.05$ (*), $p < 0.01$ (**), and $p < 0.001$ (***). Hazard ratios and 95% confidence intervals generated using the 'ggforest' function in the R package *survminer* (Kassambara et al. 2017).

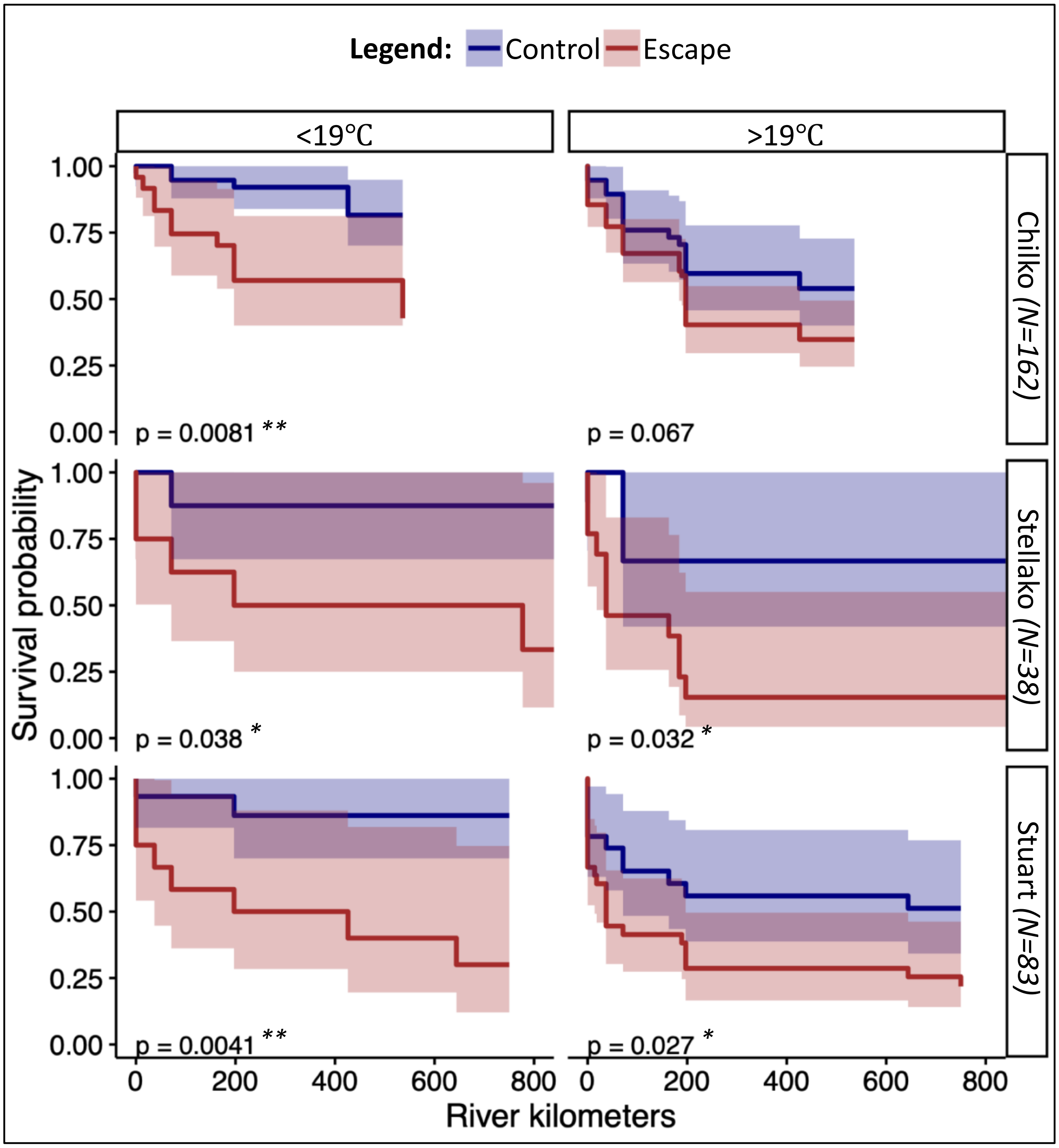


Figure 5-6 Sockeye salmon survival curves for escapees versus control fish, facetted by water temperature (horizontal) and major stock (vertical), displayed over distance in river kilometers. Significance levels shown based on log-rank tests comparing survival curves; significance shown at $p < 0.05$ (*) and $p < 0.01$ (**). Plots and 95% confidence intervals generated using the 'ggsurvplot' function in the R package *survminer* (Kassambara et al. 2017).

5.8 Tables

Table 5-1 Scoring of injury and behavioural impairment in sockeye salmon following experimental escape treatments (used in survival models as response variables).
Injury categories were assigned following (Nguyen et al. 2014). Impairment scores were tabluated as the total number of reflexes impaired (Raby et al. 2012).

	Observation	Description
Injury	Minor	Faint net marks, surface wounds, <5% scale loss
	Moderate	Visible and shallow net marks or wounds, 5-20% scale loss
	Severe	Deep and dark net marks or wounds, >20% scale loss
Impairment	Tail grab	Does the fish burst swim in response to contact?
	Orientation	Does the fish maintain equilibrium in water?
	Vestibular-ocular	Does the fish's eye roll when its body is rotated?
	Body flex	Does the fish attempt escape when restrained?
	Head complex	Does the fish exhibit regular ventilation patterns?

Table 5-2 Locations, dates, and methods used for opportunistic mobile tracking of radio-tagged sockeye salmon in the Fraser River in 2017.

Locations	Dates	Method(s)
Harrison Lake	Oct. 17 & 30	Truck
Chilko Lake	Sept. 30 & Oct. 1	Raft
Horsefly River	Sept. 20 & 21	Raft, truck, walk
Tachie River	Sept. 23 & 25	Boat, walk
Middle River	Sept. 24	Boat
Stellako River	Sept. 27	Raft

Table 5-3 Stationary telemetry receivers used to detect homing adult summer-run sockeye salmon in the Fraser River in 2017.
Table includes distance from the tagging site (Peters Road; 128 river km from the ocean), estimated detection efficiency, and site operator (UBC = University of British Columbia; DFO = Fisheries and Oceans Canada; FLNRO = BC Ministry of Forests, Lands, and Natural Resource Operations). 'NA' indicate no upstream tracking data available to estimate detection efficiency.

Station	Name	River (*confluence*)	Kms from release	Estimated efficiency	Operator
1	Fallback	Fraser	-1	100%	UBC
2	Hope East	Fraser	14	88.9%	
3	Hope West	Fraser	18		
4	Qualark	Fraser	37		
5	Hell's Gate	Fraser	71	95.0%	
6	Spences Bridge	Thompson (*Nicola*)	163	NA	
7	Confluence	Fraser (*Seton*)	184	99.1%	
8	Seton Dam	Seton	189	NA	
9	Xwisten	Fraser (*Bridge*)	197	98.6%	
10	Alexis Creek	Chilcotin	426	94.5%	EWatch
11	Lingfield	Chilko	524	97.4%	
12	Chilko Lake	Chilko	534	98.7%	
13	Quesnel	Quesnel	597	94.1%	
14	SCWA	Nechako	644	96.4%	FLNRO
15	Lower Stuart	Stuart (*Nechako*)	733	100%	
16	Upper Stuart	Stuart	746		
17	Vanderhoof	Nechako	777	47.1%	
18	Nautley	Nechako	833		

Table 5-4 Top five (determined by AICc rank) of survival using Cox proportional hazards regression (Coxph) models.
Water temperature is treated first as a categorical variable, and second as a continuous covariate.

Coxph model with water temperature (categorical)	Df	AICc	ΔAICc	Weight
~ Treatment + Injury + Temperature	6	1866.1	0.00	0.403
~ Treatment + Injury + Temperature + RAMP	7	1866.6	0.56	0.305
~ Treatment + Injury + Temperature + FL	7	1867.8	1.73	0.170
~ Treatment + Injury + Temperature + RAMP + FL	8	1868.5	2.46	0.118
~ Treatment + Injury	5	1877.6	11.56	0.001
Coxph model with water temperature (continuous)	**Df**	**AICc**	**ΔAICc**	**Weight**
~ Treatment + Injury + Temperature	6	1885.8	0.00	0.380
~ Treatment + Injury + Temperature + RAMP	7	1886.0	0.24	0.337
~ Treatment + Injury + Temperature + FL	7	1887.6	1.86	0.150
~ Treatment + Injury + Temperature + RAMP + FL	8	1888.1	2.26	0.123
~ Injury + Temperature	4	1895.0	9.26	0.004

Chapter 6: Indigenous knowledge of leading threats to wild Pacific salmon and aquatic health

6.1 Abstract

1) The decline or loss of a fishery can transform the nature of relationships among people, fish and place. Unpredictable or poor annual returns of wild Pacific salmon (genus *Oncorhynchus*) are posing serious challenges to linked social-ecological systems. Critical to the health, maintenance and/or recovery of salmon-based knowledge systems and salmon populations are decolonial research strategies poised to respect Indigenous intellectual traditions and affirm Indigenous control over Indigenous knowledge.
2) Through collaborative partnerships with 18 Indigenous communities and semi-structured interviews with 48 knowledge holders (principally Elders) across British Columbia's three largest salmon-producing systems—the Fraser, Skeena and Nass Rivers—we examined perceptions of (i) changes in salmon populations and fisheries catches over their lifetimes and (ii) leading threats to the survival of wild salmon now and in future.
3) On average, knowledge holders have spent more than half of a century actively engaged in salmon fishing and processing. Modern salmon catches are reported to be approximately one-sixth of what they were estimated to be historically, when knowledge holders were starting to fish between five and seven decades ago. Through a threat perception and evaluation exercise, we revealed differences in the relative rankings of various stressors in the aquatic environment. The top five threats in order

of scored weightings included: (i) aquaculture (salmon farms); (ii) climate change; (iii) contaminants; (iv) industrial development; and (v) infectious diseases. Our results also show that the single top-ranked threat varied by river region and system, suggesting that people's perceptions of key threats are highly context dependent and localized, reflecting the place-based nature of Indigenous knowledge systems.

4) Through a holistic lens, knowledge holders perceived threats to salmon equally as threats to aquatic and human health, with evidence that the relationships between people and water, and salmon and people, are being profoundly transformed.
5) Our study highlights the need for Indigenous voices, concerns and knowledges to be represented and heard at the salmon management decision-making table, and challenges existing notions of who are considered salmon experts.

6.2 Introduction

6.2.1 Indigenous Research Methodologies

"Indigenous methods do not flow from western philosophies; they flow from tribal epistemologies. If tribal knowledges are not referenced as legitimate knowledge systems guiding Indigenous methods and protocols within the research process, there is a congruency problem. Furthermore, by not recognizing Indigenous inquiry for what it is—a distinctive methodology—the political and practical quagmire will persist."
–(Kovach 2010 pg. 37)

In response to colonial research paradigms that have subjugated Indigenous peoples, knowledges, lands and waters, Indigenous research methodologies have recently emerged to center Indigenous visions and voices in research practice (Wilson 2008; Kovach 2010;

Smith 2012). As Indigenous peoples reclaim self-determination (see **Table 6-1** for glossary of key terms; Coulthard 2014), and as interest grows among practitioners of Western science in moving beyond knowledge assimilation or integration (Nadasdy 1999), we are beginning to see a rise in natural and social science research approaches and outcomes that are more respectful and responsive to Indigenous needs and priorities, and this has been at the hands of both Indigenous and non-Indigenous scholars alike (Thompson et al. 2019; Arsenault et al. 2019; Burt et al. 2020; Latulippe & Klenk 2020; McGregor et al. 2020; Chapman & Schott 2020; Westwood et al. 2020; Beveridge et al. 2020).

The foundations for Indigenous participatory community-engaged engaged research were laid by Kirkness and Barnhardt (1991), who described four "Rs" of ethical research practices for working in Indigenous contexts: respect, relevance, reciprocity, and responsibility. The application and practice of these core values leads to research that privileges Indigenous voices and respects distinct worldviews, that responds to local contexts and addresses community challenges, that strengthens Indigenous communities through equal benefit sharing and reciprocal learning and that is conducted in a so-called 'good way' where cultural protocols are honoured and power imbalances are recognized and rectified (Castleden et al. 2017; Arsenault et al. 2018). Through trust-based relationships and sustained commitment (Wilson 2008), these choices and actions culminate in research that is *with* as opposed to *on* Indigenous communities, transforming the nature and purpose of researcher–community interactions.

Indigenous communities are increasingly asserting their rights, creating their own ethical guidelines and protocols for permitting research in their territories, and research and policy instruments are being designed to protect Indigenous knowledge systems (including scientific, traditional and traditional ecological knowledges; refer to **Table 6-1**). There are perhaps as many approaches to the former as there are Indigenous nations, with protocol agreements requiring a range of procedures, from formal application processes with board or departmental reviews (for instance, that of the Haíłzaqv Integrated Resource Management Department 2015), to obtaining support from community leadership through presentations and meetings with, for example, Chief and Council (First Nations of Quebec and Labrador Health and Social Services Commission 2014) or hereditary leadership (Beveridge et al. 2020). In terms of the second element, the First Nations Information Governance Centre's OCAP® principles [Ownership–Control–Access–Possession] provide a roadmap for protecting knowledge holders and systems, reflecting a key principle outlined by the UN Declaration on the Rights of Indigenous Peoples (UNDRIP; United Nations General Assembly 2007) that explicitly protects Indigenous intellectual rights, stating that "free, prior and informed consent" must always be obtained regarding how such knowledge is collected, treated and shared. Negotiating what constitutes 'good' research protocols in a specific community context is an important first step in challenging existing power imbalances, it emphasizes self-determination, and opens up lines of communication between the researcher and the community (Smith 2012; Arsenault et al. 2018).

As we navigate this transition to a point where Indigenous communities and knowledge holders are rightful and full partners in research, there needs to be a commensurate shift away from viewing Indigenous knowledge systems as simply filling in the gaps of a Western scientific understanding, where the latter serves as the default frame of reference to which the former is added on, too often as an afterthought, or for the apparent "utility" of serving as a resource where Western scientific data are lacking (for instance, Huntington 1998). Indigenous knowledge systems and worldviews must instead "become a starting point for new research efforts" (Arsenault et al. 2018), valid in their own right, and through the application of a decolonial research framework, they can be used to furnish the values, processes and methodologies that guide and direct research (Simpson 2004).

6.2.2 Indigenous Knowledge Systems of Pacific Salmon

"We need the salmon for our survival as a distinct people. It is so connected into our lives that if the salmon disappear, so will we. We use the salmon for our rituals, food and trade, and in return we pay homage to the salmon." –(Alfred 2010 pg. 2)

Pacific salmon—fish known by a host of Indigenous names throughout their vast geographic range (genus Oncorhynchus)—have been in a state of decline in British Columbia (BC), Canada for several decades (Price et al. 2017) such that a growing number of wild salmon populations have been assessed as 'at risk' (from Special Concern [n=5 populations] to Threatened [n=3] to Endangered [n=10]) by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC; Government of Canada 2018). As both ecological and cultural keystone species, without the continued existence of salmon, ecosystems and societies alike would be entirely transformed (Willson & Halupka 1995; Garibaldi & Turner 2004). For the Nisg̱a'a Nation, which sits on the BC–Alaska border and to which the lead author belongs, salmon are vital. They shape ayuuḵhl (laws) and adaawaḵ (oral histories), they figure centrally in yukw (feasts, known externally as "potlatches"), and they are a focal point of the Nisg̱a'a Treaty (2000) which stipulates Nisg̱a'a rights tied specifically to salmon. As Nisg̱a'a and indeed many Indigenous nations identify as "salmon people" (Columbia River Inter-Tribal Fish Commission 2020), there is serious concern about what will become of salmon-linked cultures, economies, knowledges, languages, laws, wellbeing and worldviews as the annual return of these anadromous fish to rivers across the Pacific Northwest become increasingly unpredictable and, in many systems, Indigenous fisheries for wild salmon become a shadow of their former selves (Jacob et al. 2010). Critical to the maintenance and recovery of salmon-based knowledge systems and salmon populations are decolonial research strategies poised to respect Indigenous intellectual traditions and affirm Indigenous control over Indigenous knowledge (Simpson 2004).

Due to a range of institutional, cultural, philosophical, and methodological challenges (see Murray et al. 2011), Indigenous knowledge systems of Pacific salmon are notably absent from the Western-based fisheries management systems used to govern these fisheries. This is the case across Northwestern North America, said to be "drowned out, marginalized, and at times, worse, forgotten" in certain contexts (Walsey & Brewer 2018). Similar to fishers' knowledge (Johannes et al. 2000), which has gained traction in the literature at multiple points in time (see Hind 2015), the acceptance of experiential, place-based knowledges into fisheries management and policy has been largely precluded by Western scientific perceptions of such knowledge (and its study) being unquantifiable/unreliable, nonsystematic, and idealized (Davis & Ruddle 2010)[12].

This research is positioned to address these two separate challenges. We employ Indigenous research methodologies to document and mobilize Indigenous knowledge systems of Pacific salmon on Indigenous terms. We also detail the systematic approaches

[12] Although this predates the mainstreaming of responsive natural and social science research noted above.

undertaken herein to address three management-relevant questions based on our awareness that Indigenous knowledge systems are not uniform, and given their place-based nature, they will reflect localized contexts. Our three main lines of inquiry included: RQ1 – Have Pacific salmon populations and fisheries catches changed over time and, if so, how? RQ2 – What are perceived as leading aquatic threats to Pacific salmon survival now and in future? RQ3 – How do RQ1 and RQ2 vary by region and across BC's largest salmon-bearing river systems?

6.3 Methods

6.3.1 Developing Research Partnerships and Protocols

This research (see **Figure 6-1** for methodological workflow) emanates from a long-term research program (with leadership and involvement from all co-authors) centered on Pacific salmon ecology and conservation, using tools and understandings primarily from the natural and social sciences, with only more recent contributions from Indigenous science (by way of the lead author). Through this program, our team has built a network of collaborators (~80 representatives from other research groups, First Nations, environmental non-governmental organizations, governmental agencies and stakeholders) who convene each year at the University of British Columbia for an 'Annual Research Symposium' on salmon migrations, ecology and management (entering its 15th consecutive year; Cooke et al. in review). This workshop provides an opportunity for collaborators to offer feedback on research and recommend directions for future work, helping also to maintain research relationships in between field seasons. The need for and interest in the present study was identified through discussions here in February 2017 and

February 2018 (stemming also from previous research by our team: Jacob et al. 2010; Nguyen et al. 2016), and the symposium has since served as a platform for sharing preliminary results from this work and addressing interim questions and ideas.

From this large network and based on existing research relationships with Indigenous communities across BC's three largest salmon producing river systems, the Fraser, Skeena and Nass Rivers, we initiated conversations with various First Nations (often starting with their fisheries managers with whom we have worked extensively in many cases) as well as our primary contacts with various First Nations fisheries groups (including but not limited to: First Nations Fisheries Council, Lower & Upper Fraser Fisheries Alliances, Secwépemc & Skeena Fisheries Commissions, Nisga'a Fisheries & Wildlife Department). These formative conversations identified potential community interest in this work (or occasional suggestions for additional communities to contact), they specified community needs and expectations around reciprocity and mutual responsibility in research, and they also clarified what local research protocols entailed.

These initial conversations informed how the research team prepared protocol agreements and the research proposal for community review, which also served as preliminary materials to initiate the ethics review process with affiliated universities. Communities were invited to begin compiling lists of key knowledge holders with respect to Pacific salmon (to be shared once permissions and approvals were in place). Records were maintained to detail when community conversations took place, and at which stage of the process we were with each community. Because the Research Ethics Board (REB) process can be lengthy, it was initiated as soon as we had received and addressed feedback from potential community partners, but because no approvals had yet been sought from community partners (as in many cases, university REB approval was a prerequisite), we detailed our research practice, process and plan for the university without providing specific community partner names for the initial review. Once provisional REB approval was granted, we then completed individual community research approval processes by May 2018. These ranged from formal application processes and proposal reviews by community board members, to remote participation in community leadership meetings where objectives were explained and questions answered, to communities simply indicating no such protocols were (yet) in place and proceeding with this work would simply require individual consent from knowledge holders. Following this, we finalized our research protocol and received REB clearance in June 2018 (Carleton Ethics Clearance ID: Project # 108478; Ottawa Ethics File Number: S-06-18-853) and complete required associated training (*e.g.*, Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans (TCPS 2) – Course on Research Ethics).

6.3.2 Indigenous Knowledge Holder Interviews

Following the migratory path of adult Pacific salmon, from the coast upstream to spawning grounds, and during the time of sockeye salmon runs in BC (June to September of 2018), the lead author visited communities belonging to First Nations spread across the Fraser, Skeena and Nass Rivers (**Figure 6-2**) at which time communities of salmon practice were flourishing in places where runs were healthy and abundant that year, and notably absent in others where, for example, salmon wind-drying racks stood bare (**Figure 6-3**). By using the salmon life cycle as an epistemological tool (as with Ingersoll 2016's "seascape epistemology"), the migratory path provided an insightful means of connecting with cultures and communities, observing variations as well as points of convergence among them. Given the research objectives and key lines of inquiry described above, this research aimed to be community-engaged (*sensu* Adams et al. 2014), but not community-based which is widely understood as a cyclical and iterative process in one or few locales over long time scales (Castleden et al. 2012). To examine variation across different geographies and contexts, this 'migratory' method of research was essential.

In each partnering community, introductions were often made with a presentation at a community meeting, or in some cases at a community feast or culture camp. Between one and five community-identified knowledge holders were identified as potential 'key informants' in each community, all of which were Elders or young Elders (also referred to as Elders-in-training), recognized by their community as keepers and teachers of knowledge, not simply individuals above a certain age threshold or belonging to any specific gender identity or career path. Additional inquiries were made within each community (outside of leadership) about recommended knowledge holders to speak with, but this practice did not yield additional names not previously identified, instead it provided a secondary (often a tertiary) confirmation of who the community considers to be key knowledge keepers. Carleton University's "Guidelines for Working with First Nation, Métis and Inuit Elders and Knowledge Keepers" were followed throughout the research process (Centre for Indigenous Initiatives 2018).

Community-identified individuals were invited to participate in semi-structured interviews on the state and future of Pacific salmon. Interviews were voluntary, and written or oral consent were equally allowed. Each interview was initiated by the researcher reading aloud the key consent form elements: research purpose; data security and confidentiality measures; right to withdraw; compensation plan; permissions to be audio-recorded and photographed; and copyright sharing agreement details. For this latter element and in line with OCAP guidelines, individuals retained control of their knowledge and could opt to require being contacted before any future direct uses of their knowledge for details and approvals, and they could also agree or decline to having their interview materials contributed to their First Nations' archives (once transcribed and finalized). Interviews took place in locations of their choosing, primarily in their homes, on occasion in public spaces such as the band office or community hall, and infrequently in "atypical" locations (*e.g.*, riverside, smokehouse, four-wheeler, canoe). Participants were presented with a small gift (a jar of homemade raspberry jam or bear grease salve) at the start of each interview and were offered an honorarium to recognize time taken away from other roles and responsibilities at interview end (as outlined in each research agreement).

Semi-structured interviews lasted 0.5-2.5 hours, as determined by the knowledge holders. All interviews took place in English (although the research team was prepared to hire translators if knowledge holders preferred to speak in their native language). We approximately followed the interview guide, pivoting where necessary in response to what knowledge holders wished to share, and given their role(s) in their community (*i.e.,* a former commercial fisher could provide insight on various changes in salmon catch over time, whereas those engaged in food processing could do the same for changes in fish condition and health). Conversations were free-flowing, with only a portion focused on the above-listed research questions (specific details follow). Much of the knowledge shared was recorded for the purpose of community access in the long term.

RQ1- and RQ2-related questions were qualitative and quantitative in nature (see template questions in **Table 6-2**). The approach for RQ1 involved sub-questions posed in reverse-chronological order, starting with the present state and gradually progressing backwards in time. To gauge perspectives on changes in the state of Pacific salmon, knowledge holders were simply asked whether or not they had witnessed changes in salmon abundance over their lifetimes, and to describe those changes if applicable. Similar to Eckert et al. (2018), knowledge holders felt comfortable contrasting their catches from when they began fishing (hereafter 'historical') to now or when they stopped fishing (hereafter 'modern'). Historical values were associated with years spanning the 1950s to 1970s (thus ~50-70 years ago), and modern values were all in reference to within the last decade. To examine change in salmon catch, historical values were set as a benchmark of '1' against which the modern state could be compared as a relative proportion per individual.

For RQ2, the first sub-question was posed as an opportunity to identify leading threats before being influenced by the pre-listed threats in the second sub-question (a free listing elicitation exercise; Weller & Romney 1988). For the second sub-question, knowledge holders were presented with each pre-identified threat listed on a cue card, laid out in a randomized order. They were first asked to identify their top five concerns (including an 'other' category which, if selected, they needed to specify; 'other' could be selected up to five times, if desired). Once top selections were made, knowledge holders were invited to organize threats in order of relative importance. The threats presented reflected an amalgam of global leading freshwater threats (from Reid et al. 2019) and major stressors identified through the *Cohen Commission of Inquiry into the Decline of Sockeye*

Salmon in the Fraser River—Final Report (Cohen 2012) which included testimony by diverse knowledge holders. A weighted score was produced for each threat, accounting for the number of times each threat was selected among the top five priorities and in which priority position it was placed (scored 0-1; **Table 6-3**).

At the end of each interview, knowledge holders were asked whether they had questions pertaining to the state and future of Pacific salmon (particularly from a Western scientific standpoint). Their responses were recorded, and answers were researched and returned to them where possible. Most interviews were conducted individually, four interviews were in pairs, and two took place in small Elders' groups; for the latter two cases, responses could be given individually or through consensus. Interviews were transcribed with help from three university undergraduate students, and responses were coded according to main themes. Using Microsoft Excel, responses were categorized and tallied for qualitative analysis and to inspect for variation with respect to RQ3. R statistical software was used to visualize quantitative results (version 3.6.3 R Core Team 2017).

6.4 Results

6.4.1 Community and Knowledge Holder Engagement

Across the research visits in 18 First Nations communities, 48 knowledge holders took part in semi-structured interviews between June and September 2018, with one phone interview in November 2018 (**Figure 6-2**). This included 31 men and 17 women, ages 56 to 93. Individuals self-identified as belonging to the Nations of the Katzie, Nat'oot'ten (Lake Babine), Nisga'a, Peters, Stó:lō, Secwépemc (Shuswap), St'át'imc, Tŝilhqot'in, Ts'msyen (Tsimshian) and xʷməθkʷəy̓əm (Musqueam; English spellings provided where still commonly used). Communities were spread across the Fraser, Skeena and Nass Rivers, encompassing regions categorized as 'Lower' (the first communities in the study to encounter return-migrating salmon), 'Middle' (the second) and 'Upper' (the third). These are not true positionings within the watershed, but rather the order by which salmon (and thus the lead author) came into contact with communities in 2018. While we worked towards geographical breadth in this research, where interviews took place is reflective of where our partnerships were situated. This was not considered a comprehensive or exhaustive approach given the existence of ~200 BC First Nations—most (if not all) of which are touched by salmon. No community that we engaged with declined interest in this work; although one potential community partner along the Skeena River experienced the loss of a community member, making it unsuitable for our research to proceed there.

Also notable, no individual knowledge holders declined participating in this research and none abstained from having their interviews be audio-recorded or a profile photograph taken (for the purposes of being included in community archive packages and/or printed and returned to them alongside interview materials). There was widespread interest in contributing interview materials in both written and oral formats to community archives. Excluding the four instances where no such archives exist (or are soon to be developed), 86% of participants consented to this arrangement and 14% declined (exclusively in two regions where hereditary leadership remains strong, but community archives reside with elected band councils). All knowledge holders opted to retain control of their knowledge, as described above.

6.4.2 Change and Threat Evaluation

In response to RQ1 sub-questions, we confirmed that all knowledge holders were active participants (past and/or present) in salmon fishing and/or processing. All began fishing from a very young age (mean = 6 years old), with *"since I could walk"* (or an equivalent variant) being the most common response. On average, women had fished for 52 years and men 57 years of their lives. 71% recounted learning to fish from their parents, 23% from their grandparents, and 6% from older siblings. Set and drift gillnets were the most common fishing gear type used (64%), followed by dipnets (22%), hook and line (8%) and lastly seine nets (by former commercial fishers, 6%). With one exception—a knowledge holder from the Upper Skeena who reported no change in the state of salmon in their region—all other knowledge holders reported witnessing negative changes in salmon abundance over their lifetimes of fishing and living in their territories. Based on estimates of historical and modern salmon catch sizes from 26 respondents who felt confident providing such values, an average 83% decline was reported. Comparing, on a relative basis, modern catch sizes against historical ones revealed consistently low values across Lower, Middle and Upper river regions (except for two outliers in Upper regions; **Figure 6-4A**), and when examined by river, this revealed slightly lower values for the Fraser, greater variation across the Skeena, and slightly but consistently higher values for the Nass (**Figure 6-4B**).

All knowledge holders contributed to RQ2. In 81% of cases, threats that were free listed were also found within the threat list developed for the second sub-question, with the majority of responses centering on aquaculture (specifically salmon farms; 29%), climate change (17%), commercial fisheries (15%) and industrial development (11%).

Contaminants, hydropower projects, illegal harvest and infectious diseases accounted for another 10% of free-listed responses. The other threats put forward included multiple variants that can be grouped as ‘mismanagement’ (8%; bad fisheries management decisions, Indigenous exclusion and weak governance structures), ‘predators’ (6%; primarily marine mammal predation) and ‘capitalism’ (4%; where greed or financial ends are prioritized above all else).

Selecting top concerns from the predetermined list yielded slightly different outcomes. Based on weighted scores, the five main concerns across the study were: (i) aquaculture (hereafter salmon farms); (ii) climate change; (iii) contaminants; (iv) industrial development; followed by (v) infectious diseases (**Table 6-3**). When partitioned by river region, different top priorities emerged. Salmon farms carried the most weight among knowledge holders in Lower regions, contaminants were the leading concern in the Middle, while climate change and industrial development tied for first in the Upper (**Figure 6-5A**). Climate change and commercial fisheries were the two threats common to all ‘top five’ threat lists across regions. A few notable distinctions include heightened concern for predators in the Lower river, hydropower in the Middle, and capitalism in the Upper. By river, knowledge holders placed the most weight on contaminants in the Fraser, on industrial development in the Skeena, and on salmon farms in the Nass (**Figure 6-5B**). Salmon farms and climate change were common to the top five threat lists for each river. Finally, a few notable distinctions here included concern for commercial fisheries in the Fraser, as well as for recreational fisheries and mismanagement in the Nass. The top five priorities selected by Skeena-based knowledge holders matched those threats identified as carrying greater weight across the study as a whole.

While these lines of inquiry were specific to changes in Pacific salmon populations, associated responses frequently grew well beyond this specified scope. A number of themes emerged, and a few examples are described in **Table 6-4**. One additional theme raised by respondents that is an extension of RQ1- and RQ2-related questions was perceived change in aquatic health more generally. 35% of knowledge holders stated that *"we used to be able to drink the river"* (or similar variants) and how now they never could. One Elder in the Upper Nass, while reflecting on the state of a lake they grew up on, said *"That lake is not even a shadow of what it was when I first looked at it in the 1950s."* The salmon and the state of the water were, for them, a connected memory: *"If the north wind was blowing down river and we were coming up, we could smell the salmon in the air. We could smell the salmon. You drink the river water, and you can taste the salmon in the river. Wow!"* Another Elder in a coastal community remarked, *"I remember the day that I used to look in the Fraser River and see the fish going up. It was clear. We used to be able to drink the water out of the Fraser."* They continued, *"We used to go down there and get a fill—a fill of the Fraser River water... Now when you look in the river, you can't even see two inches down."* Another Fraser Elder remarked *"I wouldn't even touch it now."* The story was much the same among knowledge holders in the Skeena, where one Elder said, "*We can't drink the water because of the mine,"* while another confirmed in a separate interview, *"Now we can't drink Babine Lake because of the mining. We have to buy our water and it's getting costly."*

For many knowledge holders, if not all, the health of the water, the health of the salmon and indeed the health of the people are all one and the same. This was also clearly reflected among the questions posed by knowledge holders at the end of interviews, where the most common questions raised pertained to specific infectious diseases in salmon in their area, the extent and severity of these diseases and whether they pose a threat to people. Likewise, there was much concern expressed for how specific environmental practices such as mining are affecting local fish, the water and themselves.

6.5 Discussion

6.5.1 What and How We Learned

Our study shows that the nature of salmon–people relationships is shifting. The knowledge holders interviewed through this research have lived lives profoundly marked by salmon, spending on average more than half of a century actively engaged in salmon fishing and processing. Modern salmon catches are reported to be just a fraction—approximately one-sixth—of what they were estimated to be historically, when knowledge holders were just starting out fishing between five and seven decades ago. Through a threat perception and evaluation exercise, we revealed differences in the relative rankings of various stressors in the aquatic environment. The top five threats in order of scored weightings included: (i) aquaculture (salmon farms); (ii) climate change; (iii) contaminants; (iv) industrial development; and (v) infectious diseases. When partitioned by river region and system, climate change was the only stressor common to all 'top five' threat lists. Our results also show that the single top weighted threat varied by both river region (Lower=salmon farms; Middle=contaminants; Upper=climate change and industrial development) and system (Fraser=contaminants; Skeena=industrial development; Nass=salmon farms), suggesting that people's perceptions of key threats are highly context dependent and localized. Finally, through this work, knowledge holders had the space to speak to more than strictly salmon, and it was made clear that holistic aquatic health is a leading concern, with evidence that relationships between people and place—namely with lake and river systems—is transforming from a state where they once could be consumed without question to a present circumstance where the water can neither be drank nor touched in particular regions. Knowledge holders in many areas must now participate instead in a transactional relationship with water where it must be purchased for safe consumption due to a lack of potable drinking water in their First Nations communities (a state of affairs not uncommon across Indigenous communities in Canada where ~30% of community water systems are classified as "high risk" and water-borne infection rates are 26 times higher than the national average; Patrick 2011).

As many Indigenous teachings tell us *how* you learn is just as important as (if not more important than) *what* you learn (Simpson 2004), it is crucial to have placed dual emphasis in this study on (i) the insights emanating from this research, as described above, as well as (ii) the deliberate methodological approach undertaken herein to arrive at these outcomes. The high degree of community and knowledge holder participation in this research reflects a focus—*the state and future of Pacific salmon*—that is a shared concern by all involved. Ubiquitous interest in retaining control over how one's knowledge is collected, treated and shared is for us an unambiguous sign of appetite for culturally responsive and ethical research practices. The widespread, albeit context-dependent, willingness to have recorded interview materials returned to community archives (in both oral and written formats) is likely reflective of knowledge holders' recognition that additional methods are needed to help maintain and recover salmon-based knowledge systems. For many of the main and emerging themes in this research, knowledge holders repeatedly expressed concern for the next generation who from their view are increasingly disengaged from traditional salmon fishing practices, related languages and associated knowledges (Emerging Theme 1, '**ET1**'; **Table 6-4**). As one Elder put it, *"That's very, very, very bad business for the whole community... Nobody is learning how to do the fish."* Safeguarding Indigenous knowledges in this way is one means of ensuring that at least aspects of these intricate, fluid and multidimensional knowledge systems remain accessible to community members now and in future generations.

6.5.2 State and Future of Pacific Salmon

Our findings echo that of other studies who report declining Indigenous access to safe, healthy and culturally appropriate food fish. For instance, in the Nuxalk Nation, there was a reported decrease of 82% in the consumption of sockeye salmon from 1981 to 2009 (*O. nerka*; from 27 to 5 kg of fish/family/year) and 66% over that same timeframe for Chinook salmon (a.k.a. spring salmon; *O. tshawytscha*; from 38 to 13 kg/family/year; Kuhnlein et al. 2013). Sockeye and Chinook, respectively, have been found to be the first and third top-consumed seafood species by coastal First Nations in BC, with both accordingly being the first and third most important sources of protein as well as other essential nutrients (*e.g.*, vitamin A, niacin, selenium) in both Indigenous men and women (Marushka et al. 2019). Projecting climate change scenarios forward, the outlook for salmon and associated fisheries continues to appear grim. Catch potentials are expected to decline by another 17-29% by 2050, with more severe cumulative declines in catch potential for First Nations at lower latitudes (*e.g.*, Coast Salish communities) than those further north (*e.g.*, Ts'msyen; Weatherdon et al. 2016). This is consistent with our finding of lower modern catch proportions in the Fraser in comparison with the more northern Skeena and Nass Rivers. From the observations and experiences shared by diverse knowledge holders here, and in light of these parallels with previous other works, it is likely that similarly staggering declines in salmon catches pervade across BC First Nations, both now and in future.

As found through the Cohen Commission Inquiry (Cohen 2012), here we find no single “smoking gun”—no isolated cause to which these precipitous declines in salmon abundance can be attributed. Instead, a range of concerns surface through this work that share near-equal weight as perceived culprits in the matter (namely, salmon farms (weight=0.15), climate change (0.14), contaminants (0.13), industrial development (0.12) and infectious diseases (0.11); **Table 6-3**). Where novel insight emerges is from the partitioning of perceived threats by river regions and systems, which reveals a context-specific nature of key concerns. Proximity and novelty could be key explanatory variables in interpreting this variation. For instance, hydroelectric projects emerge as a top concern only among the Middle grouping, and this reflects exclusively the experiences of knowledge holders whose lives and fisheries have been irreversibly transformed by the Bridge River hydroelectric complex in St'át'imc territory. Knowledge holders here detail histories of forced relocations, salmon run extinctions and the disappearance of a fishery and a way of life, leaving little guesswork as to why hydropower ranks highly as a threat in this area. In contrast, hydropower was not identified once by respondents in the undammed Nass River, where instead recreational fisheries (in both marine and fresh waters) as well as mismanagement (specified as being on a federal level) arose as novel top concerns in this system where poor salmon returns in only more recent years have made both topics current hot button issues (Taylor 2017).

The pre-identified threats presented to knowledge holders in the threat perception and evaluation exercise were focused on potential proximate causes of declining salmon stocks, however, through the inclusion of an 'other' option, knowledge holders also identified structural drivers such as capitalism and mismanagement that they perceive as problematic for salmon conservation. The two were often viewed as intertwined and standing in stark contrast to Indigenous ethics and waste avoidance principles where one takes only what one needs and no more (**ET2**; **Table 6-4**). *"You can't eat gold"* were words commonly spoken, sometimes in explicit reference to Alanis Obomsawin's famous quotation, "When the last tree is cut, the last fish is caught, and the last river is polluted; when to breathe the air is sickening, you will realize, too late, that wealth is not in bank accounts and that you can't eat money" (Osborne 1972). One Nass Elder reflected on teachings they received from their Elders, stating they *"never ever waste any food, any. They respect the land we're in, eh? The waters, the Earth. They respect the food too. They always tell you; you never get more than what you need. Only get what you can use and share with others."* Elders' teachings from generations past are being carried as a living, not past tense, memory. On the subject of how Skeena salmon are being managed or mismanaged, one knowledge holder remarked, *"I was told that money talks. It's screaming now."* They added, *"I was brought up just to take what I need, and I still do that today. When I go food fishing, once my family has their share, the rest goes to whoever wants it. I still have it in me. I want to give it to them. So we are always careful on how much we take. I remember my grandmothers told me that there was so much fish in the Nass, in the Skeena, that you can almost walk on it. It was so much, and now..."* Pre-colonization, Indigenous salmon management revolved around customary tenure systems (**ET3**; **Table 6-4**) and ceremonial and stewardship practices that relied on deep knowledge of annual fishing cycles (**ET4**) and an ability to read the land by way of indicator species (**ET5**)—practices now largely replaced by colonial and corporate systems of salmon management that many knowledge holders feel are putting the state of salmon in jeopardy.

6.5.3 Knowledge Keepers and Researchers

Important questions have been previously raised about who are considered 'local knowledge experts' (Davis & Wagner 2003) and how one goes about engaging with Indigenous knowledge holders (Battiste 2005b). This study has taken careful measures to be transparent in our research choices and methodologies for these very reasons, while reserving the space required for communities to self-determine who they consider to be the experts and stewards of salmon-based knowledges. Knowledge holders in this research included fishers, fisheries managers, fish processors, healers, historians, ceremonialists, spiritual leaders, caregivers and advocates—individuals who carry current knowledge that is fluid, dynamic and constantly responding to new phenomena (*e.g.*, emerging threats) as they arise. If we define scientific knowledge as we have done here as that which is gathered through a systematic enterprise into testable laws and principles (**Table 6-1**), these individuals can very well be described as salmon scientists, deserving of inclusion at the salmon management decision-making table. Here, we purposefully privilege these voices so they can be heard by the Western scientific community and viewed as stemming from legitimate knowledge systems and founded on worldviews that are not rendered invalid by virtue of being distinct from the philosophy of Western science.

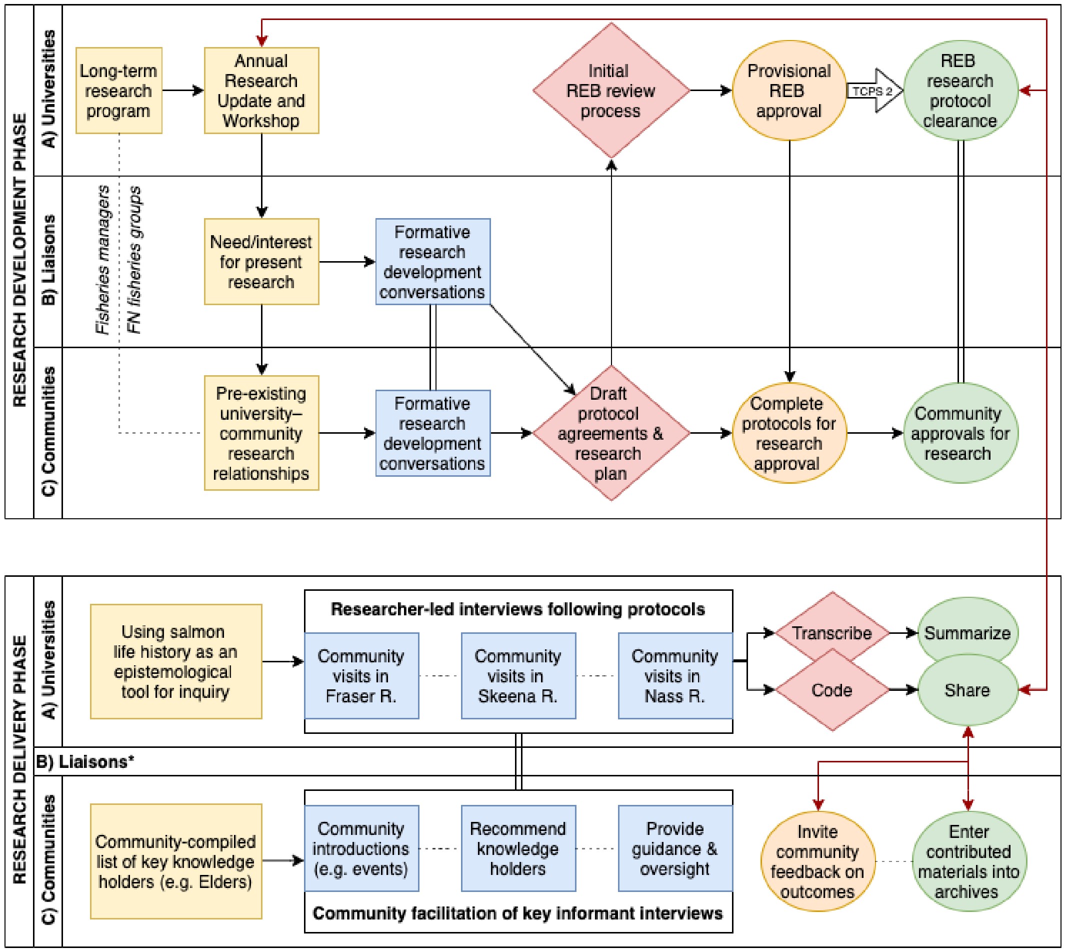
We conceptualize the research process undertaken in this study as an exercise in building and maintaining relationships. It involved a professional network of colleagues and experts, not subjects, and created an opportunity for visiting, conversations and knowledge sharing, not strictly one-way data gathering (TallBear 2014a). Following the migratory route of salmon throughout the field season meant that the research often went far beyond having recorded, deliberate interviews with knowledge holders, it involved spending time at fish camps, helping get fish home for Elders and showing up to feasts—it was in essence dedicated time to participate in salmon ceremony and culture and for these experiences to shape the research itself. It served as a legitimate mode of inquiry that yielded localized insights that otherwise would have been missed, altering the very course of conversations with knowledge holders where being able to relate to, understand and query place-based references and concerns was crucial.

Likewise, the methodological workflow, while directional and deliberate in appearance in retrospect, was not something the research team could have mapped out precisely prior to doing the work. It arose responsively as we navigated university–community relationships, as we listened to communities articulate their needs and priorities and as knowledge holders graciously welcomed the work into their homes and lives. We had also not envisioned two separate outputs (a research article and a forthcoming book project) at the outset, but this arose as one way to reconcile (i) elevating Indigenous knowledges and voices as sources of expertise in the domain of salmon science, on the one hand, and (ii) maintaining and respecting Indigenous intellectual traditions by not divorcing knowledges and stories from the rich context to which they are tied or the knowledge holders who carry them, on the other. These contextual relationships require time and space to be carefully considered, they cannot be reduced to a number as a simpler threat ranking can be and they need not be validated by external referents to be considered truth. Operating outside of the academic literature with knowledge holders as collaborators and co-authors, as will be the case with the book project, allows a great deal more flexibility to appropriately engage with these knowledges. While these were not our specific intentions at the inception of this project, their need was made clear through the research process itself. As well articulated by Kim TallBear, *"A researcher who is willing to learn how to "stand with" a community of subjects is willing to be altered, to revise her stakes in the knowledge to be produced."* (TallBear 2014b).

6.6 Conclusion

The right of Indigenous peoples to fish is one that is constitutionally protected in Canada (s.35 of the *Constitution Act*; Government of Canada 1982) and inherent to UNDRIP (Articles 25 and 29.1; United Nations General Assembly 2007), and yet there is ample evidence from this study and from across the continent (from the Mohawk Nation at Akwesasne (juncture of New York, Ontario, and Quebec) to the Ojibwe First Nations of Aamjiwnaang (near Sarnia "Chemical Valley", Ontario) and Asubpeeschoseewagong (Grassy Narrows near Kenora, Ontario) to the Yupik communities of St. Lawrence Island (in the Bering Sea, Alaska); Hoover et al. 2012; Ilyniak 2014) to show that rapidly changing fish populations due a collection of anthropogenic stressors is undermining and restricting Indigenous fisheries opportunities, fish-based knowledge systems and the very relationships between fish, people and place. We are perhaps faced with the reversal of the old adage "give a person a fish and you feed them for a day; teach a person to fish and you feed them for a lifetime.” When the fish disappear, what becomes of the associated teachings? Where do salmon-linked cultures, economies, knowledges, languages, laws, wellbeing and worldviews go as salmon dwindle—more simply put, what becomes of salmon people? The right to fish is far more than a right to eat, it is the right to practice, share knowledge, learn language and a fundamental part of who Indigenous peoples are and how they identify in Canada and around the world. As we contend with mounting environmental challenges globally, there is a need to create space for the insights, concerns and knowledges of those that live in relationship with the land waters, and who have inherent rights to access and steward them, to contribute to an enriched understanding and a more resilient path forward. In protecting the knowledge systems we are also compelled to protect the environments from which they emerged as well as the keepers who carry them. This work demonstrated one approach to engaging with salmon-based knowledge systems to bring forward Indigenous voices on Indigenous terms, but we are not alone in providing a practical example to inform how others might work towards or support Indigenous resurgence and self-determination. We are part of a larger movement within the scientific community that recognizes Indigenous rights and responsibilities to a healthy environment, and that embraces respectful, reciprocal and relational approaches to research that we encourage other researchers to consider, reflect on and practice.

6.7 Figures



*Remain key contacts, providing research guidance throughout the research delivery phase
FN = First Nations
REB = Research Ethics Board
TCPS 2 = Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans (2)
R. = River

Figure 6-1 Swimlane diagram detailing the methodological workflow for the research development phase (top) and delivery phase (bottom) for a research team involving university scholars, community liaisons, and Indigenous community partners.
Black arrows show the directional, stepwise nature of research development and delivery activities; dashed lines indicate interconnections; double bars show where activities are working in necessary parallel; and red arrows show the flow of research outcomes.

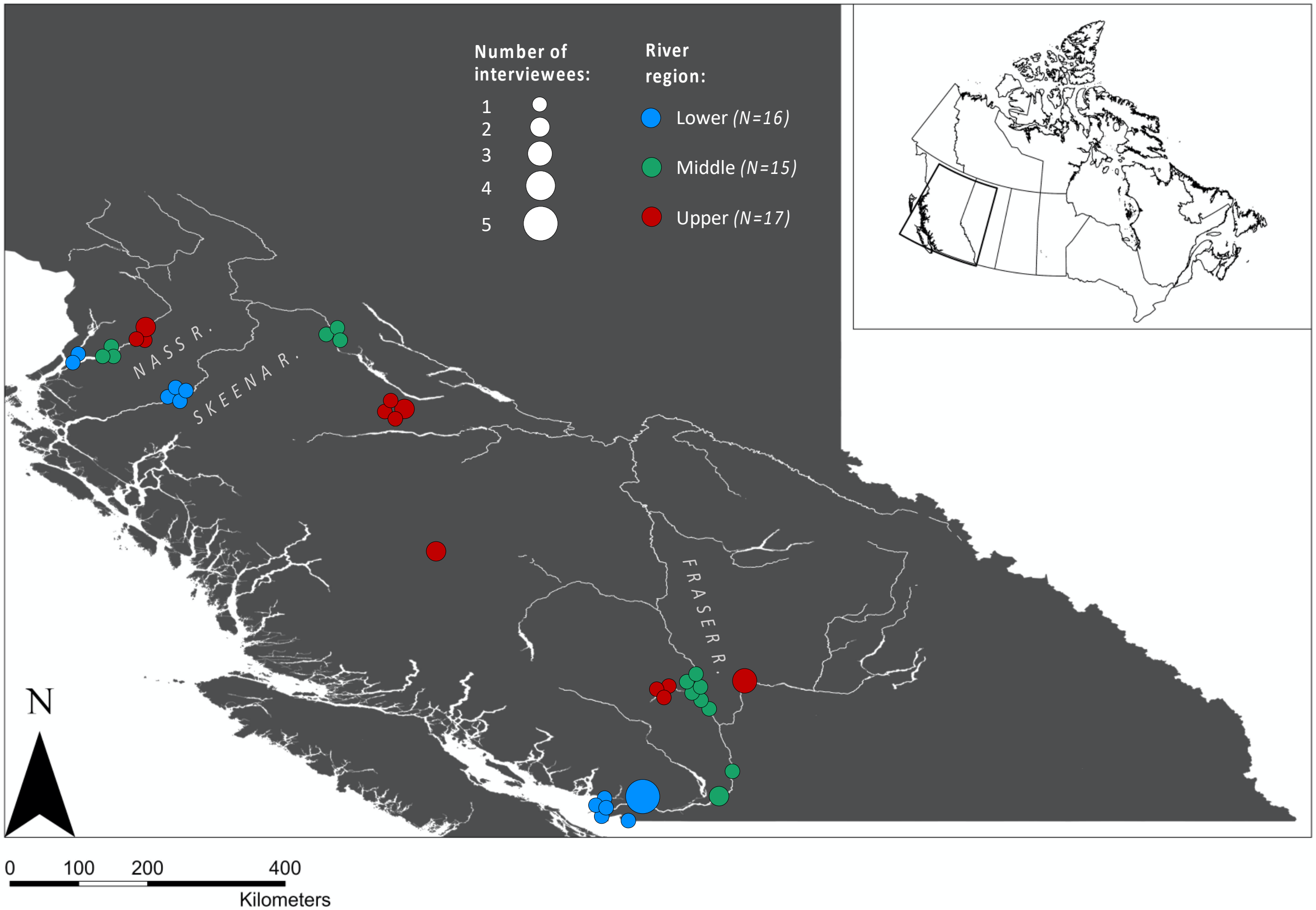


Figure 6-2 Map of British Columbia's three largest Pacific salmon producing river systems (Fraser, Skeena and Nass Rivers), showing the locations where semi-structured interviews with 48 Indigenous knowledge holders took place in June-November 2018.
River regions were categorized as 'Lower' (the first communities in the study to encounter return-migrating salmon), 'Middle' (the second) and 'Upper' (the third)––these are not true positionings within the watershed, but rather the order by which salmon (and the lead author) came into contact with communities in 2018. Geospatial data used to create this map are from the British Columbia Freshwater Atlas (Ministry of Forests, Lands, and Natural Resource Operations 2011).

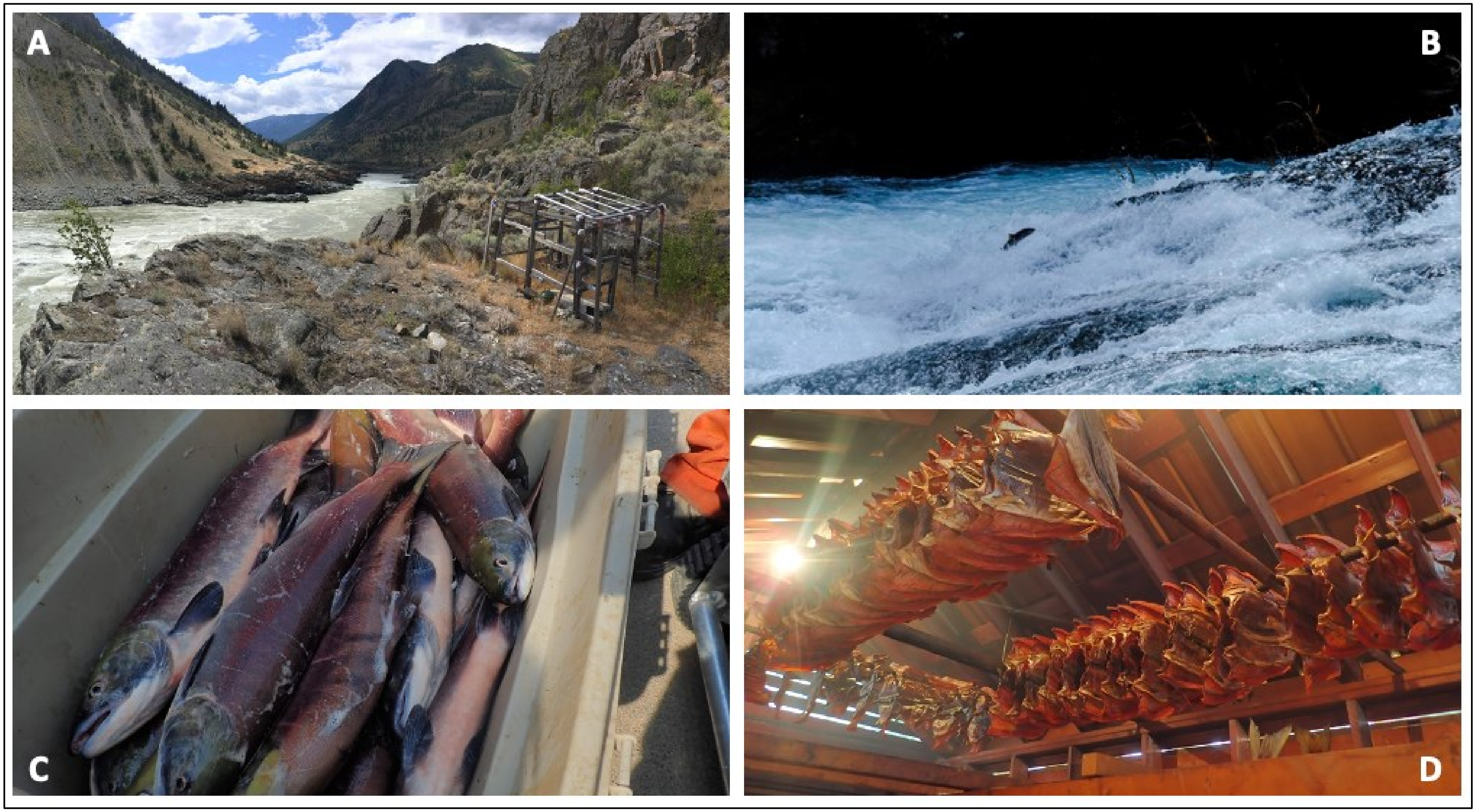


Figure 6-3 Images taken during the 2018 field season, where the life cycle of Pacific salmon was employed as an epistemological tool.
With permission, all photos were taken by the lead author from the territories of the: (A) St'át'imc Nation, Xwísten fishing grounds along the Fraser River, where a salmon wind-drying rack stands bare; (B) Nisga'a Nation along the Meziadin River, a tributary of the Nass, where a salmon attempts jumping waterfalls near spawning grounds; and (C) and (D) Lake Babine Nation, where plentiful Skeena River sockeye salmon (*Oncorhynchus nerka*) have been caught for a local Elder, and stripped and hung to dry in a smokehouse, respectively.

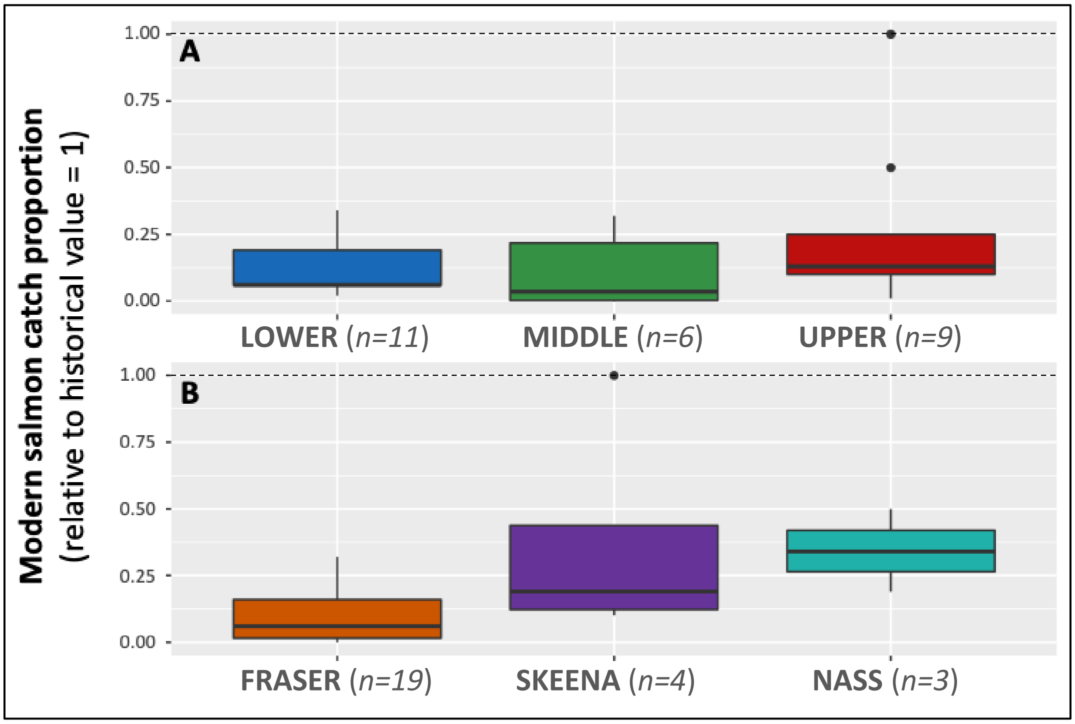


Figure 6-4 Relative proportion of Pacific salmon catch by river region, A, and system, B, as perceived by Indigenous knowledge holders.

Historical values of catch (from the 1950s-1970s, reported in the form of number of fish per unit of time) were used as benchmark (set to '1', demarcated by horizontal dashed line) against which modern values (also reported as fish per unit of time) could be compared as a relative proportion per individual (*N=26*). For example, a transition from catching 200 salmon per week historically, to catching 50 salmon per week contemporarily, is described as having a relative catch proportion of 25% (or, equivalently, a 75% decrease).

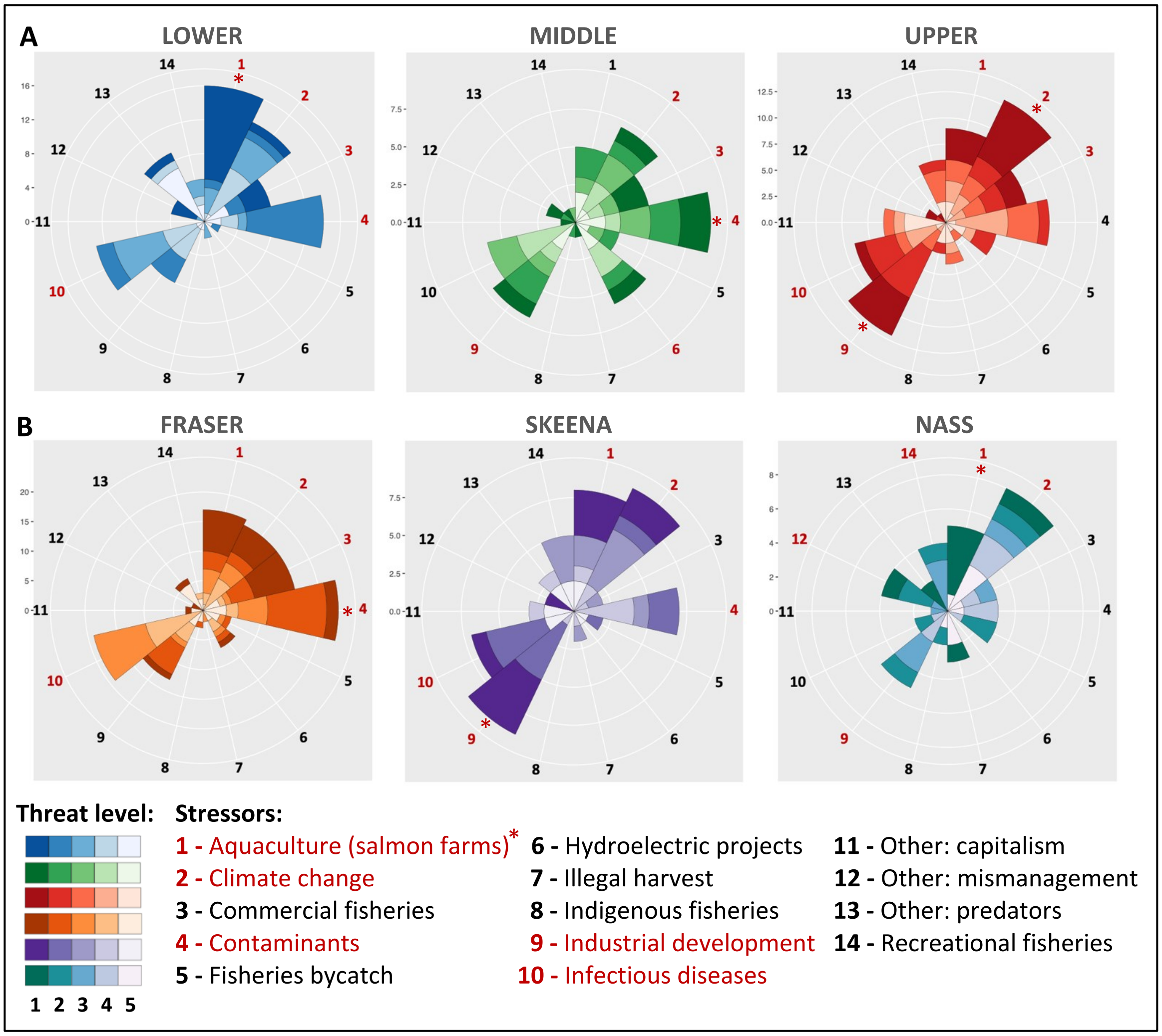


Figure 6-5 Rose plots displaying the frequency distributions of leading threats to Pacific salmon survival, as perceived by Indigenous knowledge holders, by river region (A: Lower; Middle; Upper) and system (B: Fraser; Skeena; Nass).

Hue, from darkest to lightest, indicates listing in the first position (number one priority) to last position (number five priority), respectively. Based on weighted scores (presented in **Table 6-3**), the top five priorities per grouping are identified in red font (and for the study as a whole, within the legend), and red asterisks indicate the top scoring threat per grouping (with two tied for first in the Upper region).

6.8 Tables

Table 6-1 Glossary of key terms (in order of appearance in the main text).

Key term	Definition
Self-determination	*The right of Indigenous peoples to freely determine their political status and pursue economic, social and cultural development*[1]
Western science	*Scientific knowledge with roots in the philosophy of Ancient Greece and the Renaissance, favouring reductionism and physical law*[2]
Indigenous knowledge	*Knowledge created and/or mobilized by Indigenous peoples that may include traditional knowledge and scientific knowledge*[3,4,5]
Scientific knowledge	*Systematic enterprise that gathers and condenses knowledge into testable laws and principles*[2]
Traditional knowledge	*Longstanding knowledge, practice, and belief, developed from experience gained over centuries and adapted to the local culture and environment, handed down through the generations*[5]
Traditional ecological knowledge	*Relates to the relationship of living beings (including humans) with one another and with their environment*[5]
Indigenous science	*Scientific knowledge of peoples who, as participants in culture, are affected by the worldview and interests of their home community*[6]

Sources: [1](United Nations Human Rights Office of the High Commissioner 1976); [2](Wilson 1999); [3](Arsenault et al. 2018); [4](TallBear 2014b); [5](Berkes 2018); [6](Snively & Corsiglia 2016).

Table 6-2 Template questions pertaining to RQ1 and RQ2 for semi-structured interviews.

RQ	Template questions
1	*Were (or are) you active in Pacific salmon fishing and/or processing?* *Have salmon changed in abundance over your lifetime? Please describe.* *How long has it been since you last were out salmon fishing?* *How many salmon did you catch then? (as a unit of fish/time, e.g., 10 fish per day)* *How old were you when you first went salmon fishing?* *Who taught you how to salmon fish?* *What is the main gear type you used for salmon fishing?* *When did you start fishing on your own?* *How many salmon would you catch then? (as a unit of fish/time, e.g., 10 fish per day)*
2	*What is a key threat endangering Pacific salmon populations?* *From these 12 potential threats, select your five top concerns. Next, rank them 1-5.* • *Aquaculture (salmon farms)* • *Climate change* • *Commercial fisheries* • *Contaminants* • *Fisheries bycatch* • *Hydroelectric projects* • *Illegal harvest* • *Indigenous fisheries* • *Industrial development* • *Infectious diseases* • *Other (specify; can select up to 5x)* • *Recreational fisheries*

Table 6-3 Weighted scores for leading aquatic threats as perceived by Indigenous knowledge holders, displayed for the study as a whole (global), by river region (Lower, Middle, Upper) and system (Fraser, Skeena, Nass).
The top five priorities per grouping are identified in red font, and asterisks indicate the top scoring threat per grouping (with two tied for first in the Upper region).

Aquatic threat	Global	Lower	Middle	Upper	Fraser	Skeena	Nass
1 - Aquaculture (salmon farms)	*0.15	*0.25	0.08	0.10	0.16	0.14	*0.16
2 - Climate change	0.14	0.12	0.12	*0.18	0.13	0.17	0.14
3 - Commercial fisheries	0.10	0.09	0.10	0.10	0.15	0.03	0.04
4 - Contaminants	0.13	0.16	*0.17	0.09	*0.18	0.11	0.04
5 - Fisheries bycatch	0.03	0.02	0.05	0.04	0.02	0.03	0.07
6 - Hydroelectric projects	0.03	0.00	0.09	0.01	0.04	0.01	0.00
7 - Illegal harvest	0.03	0.02	0.03	0.03	0.01	0.03	0.05
8 - Indigenous fisheries	0.02	0.00	0.02	0.02	0.01	0.00	0.04
9 - Industrial development	0.12	0.07	0.12	*0.18	0.09	*0.21	0.10
10 - Infectious diseases	0.11	0.12	0.08	0.10	0.12	0.13	0.04
11 - Other: capitalism	0.02	0.00	0.03	0.03	0.02	0.02	0.02
12 - Other: mismanagement	0.05	0.06	0.05	0.03	0.02	0.06	0.12
13 - Other: predators	0.03	0.05	0.03	0.02	0.02	0.02	0.07
14 - Recreational fisheries	0.04	0.04	0.02	0.06	0.01	0.06	0.10

Table 6-4 Example emerging themes arising from semi-structured interviews with Indigenous knowledge holders across the Fraser, Skeena and Nass Rivers in 2018.

No.	Theme	Brief description
1	Concern for next generation	*Apparent loss of language and limited knowledge of traditional salmon fishing practices among youth; concern for knowledge maintenance.*
2	Waste avoidance principles	*Not wasting any part of salmon, showing reverence by returning bones to the river, keeping what one catches and taking only what one needs.*
3	Customary tenure systems	*Families hold stewardship responsibilities for a delineated area, passed down across generations, often matrilineally.*
4	Fishing annual cycle	*The chronological return of salmon and other anadromous fishes was used to describe the annual cycle of fishing practices and traditions.*
5	Use of indicator species	*Identifying other organisms as signaling the return of the salmon each year, or ideal conditions for processing salmon.*

Chapter 7: General Conclusion

This thesis investigated leading threats to aquatic ecosystems (**Chapter 2**) and specifically to Pacific salmon (**Chapter 6**), examining how multiple stressors influence the ultimate fate (*i.e.,* survival to spawning grounds) of salmon following either their release (**Chapter 4**) or escape (**Chapter 5**) from conventional fishing gears used throughout their range. Motivated by the Mi'kmaw conceptual framework of "Two-Eyed Seeing" (reviewed in **Chapter 3**), this thesis is able to draw on the strengths and methodologies of both Indigenous and Western sciences with the aim of improving our understanding of the state of, and actionable solutions for, salmon populations and fisheries sustainability. From a mechanistic standpoint, salmon were an ideal focal system given their linear migration path and semelparous life history, making their fate relatively straightforward to monitor and evaluate which has also made them the focus of much previous related research enabling results comparisons. From a social-ecological perspective, and through an Indigenous lens, salmon are almost without parallel, making them a natural fit for these investigations.

This work has benefitted greatly from collaborations with international freshwater scientists (**Chapter 2**), thought leaders in the realm of Indigenous science (**Chapter 3**), Pacific salmon fishers and managers throughout much of the range of salmon in BC (**Chapters 4** and **5**) and Indigenous knowledge holders spread across BC's largest salmon producing systems (Nass, Skeena and Fraser Rivers; **Chapter 6**). The theoretical, applied and methodological contributions made through this work would not have been possible without these collaborations, nor could this process ascribe to a decolonial approach without the rightful and equitable inclusion of Indigenous partners and ways of knowing.

Building from foundations previously laid (Dudgeon et al. 2006), my collaborators and I show through this work that a great many stressors are putting freshwater biodiversity in jeopardy, with populations of monitored freshwater vertebrates declining by an average of 83% between 1970 and 2014 (**Chapter 2**). This chapter also identifies hopeful prospects for freshwater conservation (*e.g.*, dam removals, regulatory instruments) but advocates that a precautionary approach is necessary for managing freshwater populations in the midst of multiple stressors and extreme context dependence where one-size-fits-all approaches will rarely offer much in terms of sustained conservation solutions. To envision a new path forward for fisheries research and management – which appear to be failing fish and people across a range of contexts – my colleagues and I reviewed through a case study approach the need for and operationalization of a Two-Eyed Seeing conceptual framework (**Chapter 3**). We find that many similar models of knowledge co-existence have emerged from Indigenous contexts around the world and show how Two-Eyed Seeing has transformed the nature of research and management in three fisheries/aquatic case studies across Canada. We chart a way forward for future work in this space to enable knowledge co-existence, rectify power imbalances and promote social justice in fisheries. By working in partnership with the Nisga'a Fisheries and Wildlife Department in my nation, I was able to collaboratively lead a "Two-Eyed" study on the fate of sockeye following their incidental capture and release from commercial seine fisheries on BC's North Coast (**Chapter 4**). We monitored tagged bycatch using biotelemetry and physical recaptures through fisheries monitoring platforms (*e.g.*, fishwheels, fishway). We found that one quarter of Nass sockeye did not reach their natal areas, and North Coast management models were near-immediately updated to reflect the unintended mortality caused by the commercial fishery.

An experimental fisheries approach was also applied to Fraser sockeye to simulate escape from in-river gillnet fisheries (**Chapter 5**), providing novel insight into the realistic implications of encounters with fishing gear for return migrating adult sockeye who we again monitored using biotelemetry. In both **Chapters 4** and **5**, adopting a multivariate analytical approach (survival analysis) allowed me to relate fate outcomes to conditions of capture (*e.g.*, time in net or how the gear was fished), characteristics of study fish (*e.g.*, size, sex, stock) and external influences (*e.g.*, water temperature, subsequent fisheries harvest). Both studies point to important potential tipping points or specific circumstances (discussed further below) that could inform fisheries management and enhance salmon survival in future. Finally, I 'bookend' this thesis with Indigenous knowledge holders' insight on leading aquatic threats, specifically for Pacific salmon (**Chapter 6**). The threats identified herein align closely in multiple instances with those identified above and elsewhere (Cohen 2012; also expanded upon below), but varying in certain important ways on context-specific levels. Surprisingly, salmon harvest rates are estimated to have declined by an identical average of 83% between approximately 1970 and 2010-2018. Despite profoundly different approaches taken and highly distinct types of expertise engaged, the parallels in findings between **Chapters 2** and **6** are profound. Rather than further contextualizing and interpreting study outcomes (which is done at the end of each chapter, **Chapters 2–6**), I will close instead with a summary of major contributions to original knowledge put forward by each work. As noted at the outset (**Chapter 1**), work at the interface of Indigenous ways of knowing and Western science is replete with challenges and important considerations for research conduct; therefore, emphasis on methodological ground gained warrants consideration alongside more fundamental or applied outcomes.

7.1 Contributions to Original Knowledge

Chapter 2:

- Shows that freshwater biota (*i.e.,* monitored populations of freshwater vertebrates) are declining at rates that outpace their marine and terrestrial counterparts.
- Identifies that fresh waters represent 'endangerment hotspots' due to convergence between high biological richness and multiple anthropogenic pressures, namely: (1) *changing climates*; (2) *e-commerce and invasions*; (3) *infectious diseases*; (4) *harmful algal blooms*; (5) *expanding hydropower*; (6) *emerging contaminants*; (7) *engineered nanomaterials*; (8) *microplastic pollution*; (9) *light and noise*; (10) *freshwater salinisation*; (11) *declining calcium*; and (12) *cumulative stressors*.
- Updates our knowledge base on the state of freshwater biodiversity, where the authoritative paper on the subject (Dudgeon et al. 2006) predates the emergence of several global concerns (*e.g.*, engineered nanomaterials, officially defined in 2011; European Commission 2011) or their profound transformation (*i.e.,* unregulated Internet sale and transfer of invasive species around the globe; Humair et al. 2015).

Chapter 3:

- Challenges knowledge dichotomies that 'other' Indigenous ways of knowing.
- While not the first to articulate that uniting Indigenous and Western sciences will improve conservation outcomes (for instance, see this recent article preprint: Ogar et al. 2020), it stands alone in exposing a path forward wherein required ontological, epistemological, axiological and methodological shifts are detailed.
- Reveals parallels among models of knowledge co-existence from Indigenous peoples across continents, finding a pronounced degree of similarity.

Chapter 4:

- Provides the first post-release mortality estimate for sockeye salmon bycatch from commercial purse seine fisheries on BC's North Coast, after which a release mortality factor was near-immediately applied to the models used to manage the fishery which previously did not account for this effect.
- Demonstrates an actionable path forward to unite Indigenous and Western fisheries methodologies that strengthens the scale and scope of data obtained.
- Reveals the high recapture potential of in-river fisheries monitoring technologies (recapturing nearly half of Nass sockeye!), providing the first evidence that salmon recaptured days to weeks after a bycatch experience are significantly more injured than co-migrating control groups.
- Recommends that commercial purse seine fisheries target smaller seine sets where fish are less crowded, can be sorted more quickly and are thus not held in the net for prolonged periods where they may sustain mortality-linked injuries. Managing fisheries based on higher female post-release mortality estimates is an advisable component of a precautionary approach.

Chapter 5:

- Reveals that sockeye that undergo escape simulations *in situ* experience higher levels of mortality than control groups in the Fraser River.
- Demonstrates a viable experimental method for simulating escape in the wild, which by its very nature is elusive and difficult to analyze.
- Shows that, for Fraser sockeye, the magnitude of mortality experienced varies with fishing method, fish injury level and water temperature at the time of capture,

implying that gains could be made if fishing used gears that minimize entanglement impacts (*e.g.*, loosely strung nets) and occurred during cooler time periods (<19ºC).

- Finds that climate change resilient stocks (Eliason et al. 2011) experience lower mortality under warmer conditions than less tolerant stocks, identifying potential for population-level selection arising from fisheries escape in a warming world.
- Recommends staggered fishery openings so pulses of more vulnerable populations can navigate the river without interference.

Chapter 6:

- Shows the place-based nature of Indigenous knowledge systems, identifying regional variation in leading threats, which include: (1) *aquaculture (salmon farms)*; (2) *climate change*; (3) *commercial fisheries*; (4) *contaminants*; (5) *fisheries bycatch*; (6) *hydroelectric projects*; (7) *illegal harvest*; (8) *Indigenous fisheries*; (9) *industrial development*; (10) *infectious diseases*; (11) *other: capitalism*; (12) *other: mismanagement*; (13) *other: predators*; and (14) *recreational fisheries*.
- Reveals that profound transformations in the nature of fish–people–place relationships have occurred and are escalating, with the health of each perceived as inextricably linked by Indigenous knowledge holders.
- Finds high willingness to participate in research of this nature as well as appetite for research protocol agreements that share control over the knowledge being shared and produced, demonstrating the importance of approaches in this area of research that are fundamentally relational and founded on trust.
- Illustrates a decolonized research methodology whereby community interests and knowledge system protection are held as primary objectives.

A highly uncertain path lies ahead for Pacific salmon, migratory freshwater fishes at large and aquatic ecosystems in general. Multiple stressors threaten their viability in both the short and long term, calling into question the wellbeing of associated peoples, cultures and knowledge systems. Considerable questions remain regarding how we effectively manage these species and systems in an increasingly uncertain future. Critical tipping points, multiple-stressor problems and how we manage these hybrid systems, so they continue to meet ecological and social ends are necessary growth areas for research. One thing that is for certain is that the state of the current ecological crisis – where scientists widely recognize that we live amidst Earth's sixth mass extinction (Barnosky et al. 2011) and where in this thesis we find evidence that freshwater biota and salmon harvest rates have both fallen to one-sixth of their levels half a century ago – demands that urgent conservation actions be taken now before there is nothing or little left to manage and protect. Fundamental to effective management and protection, both now and into the future, is our ability to use all of the best tools, insights and ways of knowing that are at our disposal which can be interwoven to produce otherwise inaccessible insights as I have endeavoured to demonstrate through this thesis.

Appendices

Appendix A Major Scholarships and Fellowships Supporting Doctoral Studies

Funding Source	**Years**
Philanthropic Education Organization Scholar Award	2019–2020
New Relationship Trust Foundation Scholarship-Doctoral	(x2) 2018–2019; 2019–2020
NIB Trust Foundation Award & Scholarship-Doctoral	(x2) 2018; 2019–2020
Ontario Graduate Scholarship-Doctoral Program	(x2) 2018–2019; 2019–2020
Nisga'a Post-Secondary Education Assistance Program	2015–2020
NSERC Indigenous Student Ambassador	(x 3) 2017; 2018; 2019
Carleton University Department of Biology-Doctoral Scholarship	2015–2019
NSERC Canada Graduate Scholarship-Doctoral Program	2015–2018
Indspire Building Brighter Futures Program-Bursaries	(x4) 2015; 2016; 2017; 2018

NSERC = Natural Sciences and Engineering Research Council of Canada;
NIB = National Indian Brotherhood.

Appendix B Indigenous Knowledge & the Environment Syllabus

Syllabus page 1 of 6:

Andrea J. Reid

Carleton UNIVERSITY
Canada's Capital University

TSES 4010A: Special Topics
ENSC 4700B: Topics in Environmental Science

INDIGENOUS KNOWLEDGE & THE ENVIRONMENT

COURSE DETAILS

Schedule	Winter 2019: January 08 to April 09 Tuesdays, 14:35–17:25
Classroom	111 Paterson Hall
Instructor	Andrea J. Reid, Ph.D. Candidate Department of Biology
Email	andreajane.reid@carleton.ca Expect responses Mon-Fri 9-5
Office hours	4438 Herzberg Laboratories Available Weds 9-12

By: AJ Reid

> "These communities are the repositories of vast accumulations of traditional knowledge and experience that link humanity with its ancient origins. Their disappearance is a loss for the larger society, which could learn a great deal from their traditional skills in sustainably managing very complex ecological systems."
>
> –World Commission on Environment and Development (1987: 114-115)

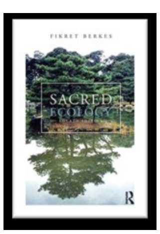
COURSE DESCRIPTION

This course will provide students with an overview of Indigenous ways of knowing with emphasis on Indigenous Knowledge (IK), and relationships between IK and Western science. This course has been designed to introduce students to the complexities and importance of IK, and to demonstrate how scientific knowledge and IK can complement each other and validate the need for interdisciplinary research to deal with complex environmental problems. Emphasis is placed on Indigenous scholarship in the course materials and guest lecturers (from Carleton unless otherwise noted).

PREREQUISITES

This course is scheduled for students with fourth-year standing or equivalent. A background in environmental science, resource management, and/or anthropology may be helpful. Parts of the course also assume some familiarity with ecology.

COURSE MATERIALS



The primary textbook for this course is:

Berkes F. (2018) Sacred Ecology. Fourth Ed. Routledge, New York, NY. 368 pp.

Weekly readings are assigned from this book; reading schedule follows below.

This book is now available in the university library (on reserve) and bookstore.

All other course readings will be provided on cuLearn.

Course Syllabus · Page 1 of 6

Syllabus page 2 of 6:

LEARNING OUTCOMES

PART I examines *Indigenous Values, Worldviews and Knowledge* in relation to the environment. At the end of Part I, students will be able to:

- Deconstruct the language used to describe Indigenous ways of knowing.
- Explain the meanings and significance (i.e. cultural, political) of IK.
- Discuss the intellectual roots (e.g. ethnoscience, biosystematics) as well as the issues (e.g. ownership, intellectual property) of applying IK.
- Describe kinds of IK systems in practice (e.g. tropical forests, uses of fire).
- Speak on how local worldviews differ from, as well as resemble, Western worldviews.
- Apply correct definitions and spellings to course assignments.

PART II explores *Ecological Applications of Indigenous Knowledge* focusing on case studies within Canada. At the end of Part II, students will be able to communicate:

- Specific examples where IK has guided environmental policy and management practices in Canada and abroad.
- A critical assessment of the associated benefits and trade-offs of applying IK.
- The broader significance of local observations and place-based research.
- Alternatives to strictly quantitative approaches to ecology;
    - Including contextual information, environmental signals, and qualitative approaches.
- Lessons for conservation/management policy and monitoring.

PART III provides a *Unifying View of Indigenous Knowledge* in a global context. At the end of Part III, students will have a working knowledge of:

- How local and traditional knowledges develop, and how they differ.
- Complex systems thinking.
- Limitations and myths surrounding IK;
    - Examples where its application has not been successful.
- How traditional and scientific knowledge may be combined.
- Adaptation and evolution of IK in a globalized world.

Syllabus page 3 of 6:

EVALUATION

Course evaluation will be based on four primary components (see evaluation breakdown below):

1. Weekly discussion of identified issues/themes/questions raised by the assigned readings for that week. Attendance and active participation for each class count. Two additional marks will be awarded for students introducing the guest lecturer to the class or leading the territorial acknowledgment (see sign-up sheet on cuLearn).
2. Students will write three 200-word responses to three exercises of their choosing from the back of the course text (pp. 339-357). These are to be submitted by the start of the corresponding class (see assignment schedule below). One bonus mark will be given to students who also submit a well-developed exercise question (no response required) that complements those presented in the course text before the end of term. Submit all works through cuLearn.
3. Group work will be carried out throughout the semester in which small groups (~4 students) will be assigned collective roles (e.g. representing a specific community, industry, environmental group, government agency etc.) as we explore two large case studies where IK has informed, or has the potential to inform, environmental policy and/or management practices, but has been met with much controversy. At the middle and end of term, groups will be brought together in simulated roundtable discussions where they will represent their researched stances in an attempt to reach agreement. Further instruction will be provided in class and on cuLearn.
4. Students will individually write one 12-page term paper (double-spaced) of an approved case study (1-page proposal required) where IK has informed, or has the potential to inform, environmental policy and/or management practices, using ideas presented in-class, guest lectures, and related activities. Further instruction will be provided in class and on cuLearn.

	Components	**Breakdown**	**Total**	**Deadline**
1	Class Participation	1% per class *x* 13 classes	13%	Throughout term
	Active Involvement	Guest intro / territory acknowledgement	2%	
2	Exercise Responses	5% each *x* 3 responses	15%	
	Exercise Question	Develop one question (no response)	1%	
3	Group Work	Evaluation by peers 5% + AJR 5%	10%	
	Roundtable Discussions	Evaluation by peers 5% + AJR 15%	20%	Feb 12; Apr 2
4	Term Paper Proposal	*Details in cuLearn guidelines*	5%	Feb 26
	Final Term Paper	*Details in cuLearn guidelines*	35%	April 9

ATTENDANCE

Regular attendance is expected. If you expect to miss more than one class during the term due to conflicting responsibilities, please discuss this with the instructor before the add/drop date. Generally speaking, missing more than 1 class during the term will negatively affect your grade.

POLICY FOR LATE ASSIGNMENTS

Accommodation can be made for students to submit assignments after the scheduled due date owing to illness, bereavement, or another legitimate reason. Alternate arrangements to complete course requirements need to be made by the student with the instructor as soon as possible. In general, cases where an assignment is submitted late and the student cannot provide a legitimate reason for the late submission, points will be deducted each day from the assignment grade (2% per day).

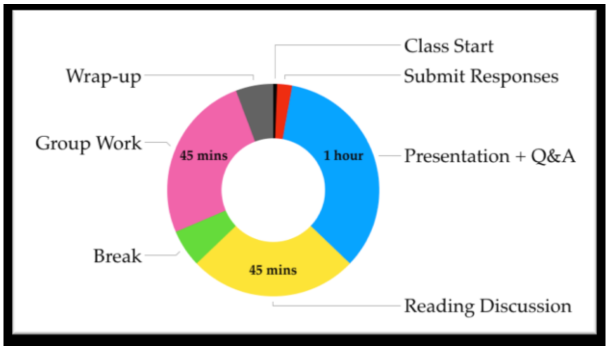
COURSE PROTOCOLS

Given the politically and often emotionally charged subject matter of this course, it is expected that students, the instructor, and guest lecturers will dialogue and generally treat one another with "respect, courtesy, honesty and good faith". At no time will comments that are racially pejorative be tolerated.

Syllabus page 4 of 6:

SEMINAR STRUCTURE

- Once (3hrs) per week
- *Presentation + Q&A* = guest/remote lecture + discussion or in-class presentations.
- *Reading Discussion* = chapter summary, group discussion + exercise review.
- *Group work* = dedicated for group work for round table exercise.



TOPICS, READINGS & ASSIGNMENTS SCHEDULE **tentative**

(guest lecturers in green | readings/resources in black | assignment deadlines and exercise options in red)

PART I: Indigenous Values, Worldviews and Knowledge

Week 1: January 8 ¤ Introduction & Overview

Reference: NativeLand (map of Indigenous language groups)
Reference: UBC (2016) Indigenous Peoples: Language Guidelines

Week 2: January 15 ¤ Context of TEK

Berkes (2018) Chp 1: pp. 1-22
Additional reading: Todd, Z. (2014) Etudes/Inuit/Studies 38: 217-238
Exercise 1 Response: pp. 341

Week 3: January 22 ¤ TEK Comes of Age

Dr. Kahente Horn Miller
Berkes (2018) Chp 2: pp. 23-56
Additional reading: Cargo et al. (2008) Health Edu Res 23: 904-914
Exercise 2 Response: pp. 342

Week 4: January 29 ¤ Intellectual Roots of TEK

Pitseolak Pfeifer
Berkes (2018) Chp 3: pp. 57-80
Additional reading: Pfeifer, P. (2018) Northern Public Affairs 6.1: 29-34
Exercise 3 Response: pp. 344

Week 5: February 5 ¤ Traditional Knowledge Systems in Practice

Lauren Eckert (University of Victoria) → Martha Attridge Bufton
Berkes (2018) Chp 4: pp. 81-108
Additional reading: Eckert, L. (2018) *Ecology & Society* 00: 000-000
Exercise 4 Response: pp. 345

Syllabus page 5 of 6:

PART II: Ecological Applications of Indigenous Knowledge

Week 6: February 12 ¤ Cree Worldview "From the Inside"

Berkes (2018) Chp 5: pp. 109-130
Simulation 1 → CUAG guided visit (3:45pm)
Exercise 5 Response: pp. 346 | Term Paper Proposal: deadline option #1

Winter Break: February 18-22

Week 7: February 26 ¤ A Story of Caribou and Social Learning

Corinne McKay (Nisga'a Nation)
Berkes (2018) Chp 6: pp. 131-154
Exercise 6 Response: pp. 348 | Term Paper Proposal: deadline option #2

Week 8: March 5 ¤ Cree Fishing Practices as Adaptive Management

Bundle – *Indigenous Environmental Relations*
Berkes (2018) Chp 7: pp. 155-178
Exercise 7 Response: pp. 350

Week 9: March 12 ¤ Climate Change and Indigenous Ways of Knowing

Dr. Janet Tamalik McGrath
Berkes (2018) Chp 8: pp. 179-202
Additional reading: Cameron et al. (2015) Ann Ass Am Geo 105: 274-283
Exercise 8 Response: pp. 352

PART III: Unifying View of Indigenous Knowledge

Week 10: March 19 ¤ Holism of Indigenous Knowledge

Dr. Karen Lawford (Queen's University)
Berkes (2018) Chp 9: pp. 203-226
Additional reading: Lawford & Giles (2012) Pimatisiwin 10: 327-340
Exercise 9 Response: pp. 353

Week 11: March 26 ¤ How Local and Traditional Knowledge Develops

Rebekah Ingram
Berkes (2018) Chp 10: pp. 227-248
Exercise 10 Response: pp. 353

Week 12: April 2 ¤ Indigenous Knowledge in Context

Jacqueline Chapman
Berkes (2018) Chp 11: pp. 249-274
Simulation 2
Exercise 11 Response: pp. 355

Week 13: April 9 ¤ Toward a Unity of Mind and Nature

Suzanne Keeptwo (Cultural Advisor, Ottawa)
Berkes (2018) Chp 12: pp. 275-298
Term Paper
Exercise 12 Response: pp. 357

Syllabus page 6 of 6:

PLAGIARISM

Plagiarism is the attempt to pass off another person's writings, images or ideas as your own work. Plagiarism is a serious offense and is subject to University policy regarding Instructional Offenses (see the section on Academic Standing and Conduct in the front of the Undergraduate Calendar). If there is clear evidence of plagiarism, then a mark of F will be awarded, and further action may need to be taken. Any questions regarding this issue should be brought to me.

ACADEMIC ACCOMMODATION

You may need special arrangements to meet your academic obligations during the term. For an accommodation request the processes are as follows:

PREGNANCY OBLIGATION

Write to me with any requests for academic accommodation during the first two weeks of class, or as soon as possible after the need for accommodation is known to exist. For more details see the Student Guide.

RELIGIOUS OBLIGATION

Write to me with any requests for academic accommodation during the first two weeks of class, or as soon as possible after the need for accommodation is known to exist. For more details see the Student Guide.

STUDENTS WITH DISABILITIES

The Paul Menton Centre for Students with Disabilities (PMC) provides services to students with Learning Disabilities (LD), psychiatric/mental health disabilities, Attention Deficit Hyperactivity Disorder (ADHD), Autism Spectrum Disorders (ASD), chronic medical conditions, and impairments in mobility, hearing, and vision. If you have a disability requiring academic accommodations in this course, please contact PMC at 613-520-6608 or pmc@carleton.ca for a formal evaluation. If you are already registered with the PMC, contact your PMC coordinator to send me your Letter of Accommodation at the beginning of the term, and no later than two weeks before the first in-class scheduled test or exam requiring accommodation (if applicable). After requesting accommodation from PMC, meet with me to ensure accommodation arrangements are made. Please consult the PMC website for the deadline to request accommodations for the formally-scheduled exam (if applicable).

You can visit the Equity Services website to view the policies and to obtain more detailed information on academic accommodation at http://www2.carleton.ca/equity.

Andrea J. Reid
Carleton University
January 2019

Appendix C Publications During Doctoral Studies

C.1 Peer-reviewed Journal Articles

Reid AJ, Eckert LE, Lane JF, Young N, Hinch SG, Darimont CT, Cooke SJ, Ban NC, Marshall A. In Press. "Two-Eyed Seeing": An Indigenous framework to transform fisheries research and management. Fish and Fisheries.

Cooke SJ, Nguyen VM, Chapman JM, **Reid AJ**, Landsman SJ, Young N, Hinch SG, Schott S, Mandrak N, Semeniuk CAD. 2020. Knowledge co-production: A pathway to effective fisheries management, conservation, and governance. Fisheries. https://doi.org/10.1002/fsh.10512

Raby G, Chapman JM, de Bruijn R, Eliason EJ, Elvidge CK, Hasler CT, Madliger CL, Nyboer EA, **Reid AJ**, Roche DG, Rytwinski T, Ward TD, Wilson ADM, Cooke SJ. 2020. Teaching post-secondary students in ecology and evolution: Strategies for early-career researchers. Ideas in Ecology and Evolution. 13:14–24. https://doi.org/10.24908/iee.2020.13.3.e

Cooke SJ, Bergman JN, Nyboer EA, **Reid AJ**, Gallagher AJ, Hammerschlag N, Van de Riet K, Vermaire JC. 2020. Overcoming the concrete conquest of aquatic ecosystems. Biological Conservation. 247: https://doi.org/10.1016/j.biocon.2020.108589

Reid AJ, Lane JF, Woodworth S, Spring A, Garner R, Tanche K. 2020. Leading on-the-land science camps with Indigenous youth: towards reciprocity in research. The Solutions Journal. 11: https://www.thesolutionsjournal.com/article/leading-land-science-camps-indigenous-youth-towards-reciprocity-research/

Carlson AK, Taylor WW, Cronin MR, Eaton MJ, Kaemingk MA, **Reid AJ**, Trudeau A. 2020. A social–ecological odyssey in fisheries and wildlife management. Fisheries. 45:238–243. https://doi.org/10.1002/fsh.10439

Castañeda RA, Burliuk CMM, Casselman JM, Cooke SJ, Dunmall KM, Forbes LS, Hasler CT, Howland KL, Hutchings JA, Klein GM, Nguyen VM, Price MHH, **Reid AJ**, Reist JD, Reynolds JD, Van Nynatten A, Mandrak NE. 2020. A brief history of fisheries in Canada. Fisheries. 45:303–318. https://doi.org/10.1002/fsh.10449

Pérez-Jvostov F, Sutherland WJ, Barrett RD, Brown CA, Cardille JA, Cooke SJ, Cristescu ME, St-Gelais NF, Fussmann GF, Griffiths K, Hendry AP, Lapointe NWR, Nyboer EA, Pentland RL, **Reid AJ**, Ricciardi A, Sunday JM, Gregory-Eaves I. 2020. Horizon scan of conservation issues for inland waters in Canada. Canadian Journal of Fisheries and Aquatic Sciences. 77:869–881. https://doi.org/10.1139/cjfas-2019-0105

Cooke SJ, Twardek WM, **Reid AJ**, Lennox RJ, Danylchuk SC, Brownscombe JW, Bower SD, Arlinghaus R, Hyder K, Danylchuk AJ. 2019. Searching for responsible and sustainable recreational fisheries in the Anthropocene. Journal of Fish Biology. 94:845–56. https://doi.org/10.1111/jfb.13935

Reid AJ, Carlson AK, Creed IF, Eliason EJ, Gell PA, Johnson PTJ, Kidd KA, MacCormack TJ, Olden JD, Ormerod SJ, Smol JP, Taylor WW, Tockner K, Vermaire JC, Dudgeon D, Cooke SJ. 2019. Emerging threats and persistent conservation challenges for freshwater biodiversity. Biological Reviews. 94:849–873.

Cook KV, **Reid AJ**, Patterson DA, Robinson KA, Chapman JM, Hinch SG, Cooke SJ. 2019. A synthesis to understand responses to capture stressors among fish discarded from commercial fisheries and options for mitigating their severity. Fish and Fisheries. 20:25–43. https://doi.org/10.1111/faf.12322

Cook KV, Hinch SG, Watson MS, Patterson DA, **Reid AJ**, Cooke SJ. 2018. Experimental capture and handling of chum salmon reveal thresholds in injury, impairment, and physiology: Best practices to improve bycatch survival in a purse seine fishery. Fisheries Research. 206:96–108. https://doi.org/10.1016/j.fishres.2018.04.021

Lynch AJ, Cowx IG, Fluet-Chouinard E, Glaser SM, Phang SC, Beard TD, Bower SD, Brooks JL, Bunnell DB, Claussen JE, Cooke SJ, Kao YC, Lorenzen K, Myers BJE, **Reid AJ**, Taylor JJ, Youn S. 2017. Inland fisheries–Invisible but integral to the UN Sustainable Development Agenda for ending poverty by 2030. Global Environmental Change. 47:167–73. https://doi.org/10.1016/j.gloenvcha.2017.10.005

Reid AJ, Brooks JL, Dolgova L, Laurich B, Sullivan BG, Szekeres P, Wood SLR, Bennett JR, Cooke SJ. 2017. Post-2015 Sustainable Development Goals still neglecting their environmental roots in the Anthropocene. Environmental Science & Policy 77:179–184. https://doi.org/10.1016/j.envsci.2017.07.006

Johnson CA, Raubenheimer D, Chapman CA, Tombak KJ, **Reid AJ**, Rothman JM. 2017. Macronutrient balancing affects patch departure by guerezas (Colobus guereza). American Journal of Primatology. 79:1–9.

C.2 Book Chapters

Reid AJ, Eckert LE, Hanna DEL. 2020. Rethinking Fisheries Leadership—On Working With and From Within Indigenous Communities. In: Taylor W, Carlson A, Bennett A, Ferreri P (Eds.), Lessons in Leadership: Integrating Courage, Vision, and Innovation for the Future of Sustainable Fisheries. American Fisheries Society (AFS) Press. In Press.

Reid AJ, Carlson AK, Hanna DEL, Olden JD, Ormerod SJ, Cooke SJ. 2020. Conservation Challenges to Freshwater Ecosystems. In: Goldstein MI, DellaSala DA (Eds.), Encyclopedia of the World's Biomes, vol. 4. Elsevier, pp. 270–278. ISBN: 9780128160961.

Brownscombe JW, **Reid AJ**, Dolgova L, Pusiak R, Laurich B, Turenne ED, Zolderdo A, Moraga A, Birnie-Gauvin K, Brooks J, Sullivan B, Ford M, Bower SD, Bennett JR, Cooke SJ. 2017. Aquatic Conservation. In: Gibson D (Ed.), Oxford Bibliographies in Ecology. Oxford University Press, New York. https://doi.org/10.1093/OBO/9780199830060-0181

C.3 Reports

Patterson DA, Robinson KA, Lennox RJ, Nettles TL, Donaldson LA, Eliason EJ, Raby GD, Chapman JM, Cook KV, Donaldson MR, Bass AL, Drenner SM, **Reid AJ**, Cooke SJ, Hinch SG. 2017. Review and Evaluation of Fishing-Related Incidental Mortality for Pacific Salmon. DFO Can. Sci. Advis. Sec. Res. Doc. 2017/010. ix + 155 p. https://dfo-mpo.gc.ca/csas-sccs/Publications/SAR-AS/2016/2016_049-eng.html

Cook KV, **Reid AJ**, Hinch SH. 2017. Evaluation of population-specific behavioural impairment and mortality in Pacific salmon incidentally captured in marine commercial purse seine fisheries. 17 p. Pacific Salmon Commission.

C.4 Articles in Review

Harper M, et al. Twenty-five essential research questions to enhance the protection and restoration of freshwater biodiversity. Freshwater Conservation: Marine and Freshwater Ecosystems.

Cooke SJ, et al. The ten steps to responsible inland fisheries in practice: Reflections from diverse regional case studies around the globe. Reviews in Fish Biology and Fisheries.

Cooke SJ, et al. Stewardship and management of freshwater ecosystems – from Leopold's land ethic to a freshwater ethic. Aquatic Conservation: Marine and Freshwater Ecosystems.

Atlas WI, et al. Indigenous systems of management for culturally and ecologically resilient Pacific salmon (*Oncorhynchus* spp.) fisheries. Fish and Fisheries.

C.5 Articles in Prep

Cooke SJ, Nguyen VM, Young N, Reid AJ, Roche D, Bennett N, Rytwinski T, Bennett JR. Contemporary authorship guidelines fail to recognize diverse contributions in conservation science research. *In prep* for Conservation Biology.

Reid AJ, Cook KV, Wale TL, Middleton CT, Bass AL, Araujo HA, Alexander RA, Hinch SG, Cooke SJ. Combining Indigenous and Western fisheries sciences links ultimate fate of sockeye salmon bycatch with conditions of commercial capture and release. *In prep* for Ecological Applications.

Reid AJ, Moulton DA, Elmer LK, Kanigan AM, Patterson DA, Robinson KA, Araujo HA, Cooke SJ, Hinch SG. Survival of sockeye salmon following gillnet escape – in search of sustainable fisheries solutions. *In prep* for Conservation Science and Practice.

Reid AJ, Young N, Hinch SG, Cooke SJ. Indigenous knowledge of leading threats to wild Pacific salmon and aquatic health. *In prep* for People and Nature.

Buxton RT, et al. From information to action: Key information needs for biodiversity conservation in Canada. *In prep* for Conservation Biology.

C.6 Popular Media

Reid AJ, Cooke SJ. 2019. Freshwater wildlife face an uncertain future. The Conversation Canada. https://theconversation.com/freshwater-wildlife-face-an-uncertain-future-108863

Wujec M, **Reid AJ**. 2015. Bumphead parrotfish conservation blog series *[n=6]*. National Geographic Society Newsroom. https://blog.nationalgeographic.org/tag/mikayla-wujec-andrea-reid/

Appendix D Media Coverage Stemming from Doctoral Studies

D.1 Broadcast Interviews

2020 Bringing 'Two-Eyed Seeing' — Indigenous Knowledge and Science — to Fisheries Conservation, Quirks & Quarks, CBC Radio https://www.cbc.ca/radio/quirks/feb-15-agriculture-moving-north-arrokoth-s-secrets-the-microbiome-for-flight-and-more-1.5463847/bringing-two-eyed-seeing-indigenous-knowledge-and-science-to-fisheries-conservation-1.5463853

2020 Riparia and Freshwater Ecology, Sisters of Sci-Fi, available on iTunes, Spotify, Google Play, and through the RSS Feed http://www.sistersofscifi.com/2020/01/21/episode-28-dalal-hanna-and-andrea-reid-riparia-and-freshwater-ecology/

D.2 Text Interviews

2020 Bringing 'Two Eyed Seeing' — Indigenous Knowledge And Science — To Fisheries Conservation, FishBio https://fishbio.com/news/bringing-two-eyed-seeing-indigenous-knowledge-science-fisheries-conservation

2019 The Best Classroom Inspiring the Next Generation of Water Protectors, Raven Magazine https://carleton.ca/ravenmag/story/water-big-blue/

2019 Young Biologist's Fish Research Strengthens Indigenous Heritage Bond, Water Today https://www.watertoday.ca/ts-fn-canadian-biologist-fish-research-strengthens-indigenous-heritage-bond.asp

2019 Carleton PhD Candidate Wins PEO Award, Carleton Newsroom https://newsroom.carleton.ca/2019/carleton-phd-candidate-wins-peo-award/

2019 Andrea Reid Accepts Assistant Professor Position at UBC, Nisga'a Lisims Government News https://www.nisgaanation.ca/news/andrea-reid-accepts-assistant-professor-position-ubc

2019 "It's at the very core of everything": The Significance of Canada's Wild Rivers, Canadian Geographic https://www.canadiangeographic.ca/article/its-very-core-everything-significance-canadas-wild-rivers

2019 Biology's Andrea Reid Wins PIR Young Researcher Ambassador Award https://carleton.ca/biology/2019/biologys-andrea-reid-wins-pir-young-researcher-ambassador-award/

2019 Fish are Facing New Kinds of Threats — But There's Hope, The Ottawa Citizen https://ottawacitizen.com/news/local-news/fish-are-facing-new-kinds-of-threats-but-theres-hope

2018 Emerging Threats and Persistent Conservation Challenges for Freshwater Biodiversity, The Freshwater Blog https://freshwaterblog.net/2018/12/21/emerging-threats-and-persistent-conservation-challenges-for-freshwater-biodiversity/

2018 Open Doors: Celebrating Research, Carleton Newsroom https://newsroom.carleton.ca/story/open-doors-celebrating-research/

2018 Ottawa Student Brings Eco-science Camp to Nisga'a Community, NSERC Impact Story https://www.nserc-crsng.gc.ca/Media-Media/ImpactStory-ArticlesPercutant_eng.asp?ID=1411

2018 Carleton PhD Student Reconnects with Indigenous Heritage through Scientific Research, The Charlatan https://charlatan.ca/2018/09/carleton-phd-student-reconnects-with-indigenous-heritage-through-scientific-research/

2018 Fish Research Links to Indigenous Heritage, Carleton Newsroom https://newsroom.carleton.ca/story/fish-research-andrea-reid/

2018 Larkin Award Recipient (PhD) – Andrea Reid, American Fisheries Society Canadian Aquatic Resources Section https://cars.fisheries.org/larkin-award-recipient-phd-andrea-reid/

2017 Salmon and Science: Sharing Grad Research with Northern Schoolchildren, Carleton Newsroom. https://gradstudents.carleton.ca/2017/sharing-grad-research-northern-school-children/

References

Abu R, Reed MG, Jardine TD. 2019. Using two-eyed seeing to bridge Western science and Indigenous knowledge systems and understand long-term change in the Saskatchewan River Delta, Canada. International Journal of Water Resources Development, DOI: 10.1080/07900627.2018.1558050

Abu R, Reed MG. 2018. Adaptation through bricolage: Indigenous responses to long-term social-ecological change in the Saskatchewan River Delta, Canada. The Canadian Geographer / Le Géographe canadien **62**:437–451.

Adams MS, Carpenter J, Housty JA, Neasloss D, Paquet PC, Service C, Walkus J, Darimont CT. 2014. Toward increased engagement between academic and indigenous community partners in ecological research. Ecology and Society **19**. Resilience Alliance Inc. Available from https://www.jstor.org/stable/26269637 (accessed July 18, 2020).

Agrawal A. 1995. Dismantling the divide between Indigenous and scientific knowledge. Development and Change **26**:413–439.

Akaike H. 1974. A new look at the statistical model identification. IEEE Transactions on Automatic Control **19**:716–723.

Alderman DJ, Polglase JL, Frayling M, Hogger J. 1984. Crayfish plague in Britain. Journal of Fish Diseases **7**:401–405.

Alexander SM, Provencher JF, Henri DA, Taylor JJ, Lloren JI, Nanayakkara L, Johnson JT, Cooke SJ. 2019. Bridging Indigenous and science-based knowledge in coastal and marine research, monitoring, and management in Canada. Environmental Evidence **8**:36.

Alfred G. 2010. Development and evaluation of "salmon–the lifeline to our culture." University of Victoria, Victoria, BC.

Allan JD, Abell R, Hogan Z, Revenga C, Taylor BW, Welcomme RL, Winemille K. 2005. Overfishing of Inland Waters. BioScience **55**:1041–1051. Oxford University Press.

Allen RB, Clinton PW, Davis MR. 1997. Cation storage and availability along a *Nothofagus* forest development sequence in New Zealand. Canadian Journal of Forest Research **27**:323–330.

Alverson DL, Freeberg MH, Pope JG, Murawski SA. 1994. A global assessment of fisheries bycatch and discards. FAO, Rome, Italy.

Anderson MK. 2013. Tending the Wild: Native American Knowledge and the Management of California's Natural Resources. University of California Press.

Arsenault R, Bourassa C, Diver S, McGregor D, Witham A. 2019. Including Indigenous knowledge systems in environmental assessments: Restructuring the process. Global Environmental Politics **19**:120–132. MIT Press.

Arsenault R, Diver S, McGregor D, Witham A, Bourassa C. 2018. Shifting the framework of Canadian water governance through Indigenous research methods: Acknowledging the past with an eye on the future. Water **10**:49.

Artelle KA, Zurba M, Bhattacharyya J, Chan DE, Brown K, Housty J, Moola F. 2019. Supporting resurgent Indigenous-led governance: A nascent mechanism for just and effective conservation. Biological Conservation **240**:108284.

Arthington AH et al. 2018. The Brisbane Declaration and Global Action Agenda on Environmental Flows (2018). Frontiers in Environmental Science **6**:1–15.

Arthington AH, Dulvy NK, Gladstone W, Winfield IJ. 2016. Fish conservation in freshwater and marine realms: status, threats and management. Aquatic Conservation: Marine and Freshwater Ecosystems **26**:838–857.

Ashforth D, Yan ND. 2008. The interactive effects of calcium concentration and temperature on the survival and reproduction of *Daphnia pulex* at high and low food concentrations. Limnology and Oceanography **53**:420–432.

Australian Institute of Aboriginal and Torres Strait Islander Studies (AIATSIS). 2012. Guidelines for Ethical Research in Australian Indigenous Studies. Canberra, A.C.T. Available from https://aiatsis.gov.au/sites/default/files/docs/research-and-guides/ethics/gerais.pdf.

Avakyan AB, Iakovleva VB. 1998. Status of global reservoirs: the position in the late twentieth century. Lakes and Reservoirs: Research and Management **3**:45–52.

Backer L, Manassaram-Baptiste D, LePrell R, Bolton B. 2015. Cyanobacteria and algae blooms: review of health and environmental data from the harmful algal bloom-related illness surveillance system (HABISS) 2007–2011. Toxins **7**:1048–1064.

Bácsi I, B-Béres V, Kókai Z, Gonda S, Novák Z, Nagy SA, Vasas G. 2016. Effects of non-steroidal anti-inflammatory drugs on cyanobacteria and algae in laboratory strains and in natural algal assemblages. Environmental Pollution **212**:508–518.

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