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Perspective

Once considered a "disruptive science", biotelemetry is now among the most trusted and relevant approaches informing salmon fisheries management

Scott G. Hinch[a], **Steven J. Cooke**[b], **and Nathan Young**[c]

[a]Pacific Salmon Ecology and Conservation Laboratory, Department of Forest and Conservation Sciences, University of British Columbia, 2424 Main Mall, Vancouver, BC V6T1Z4, Canada; [b]Department of Biology and Institute of Environmental and Interdisciplinary Science, Carleton University, 1125 Colonel By Drive, Ottawa, ON K1S 5B6, Canada; [c]School of Sociological and Anthropological Studies, University of Ottawa, 120 University Private, Ottawa, ON K1N 6N5, Canada

Corresponding author: **Scott G. Hinch** (email: scott.hinch@ubc.ca)

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Abstract

New scientific approaches that prompt a rethink in resource policy or management, and that lead to "worldviews" being challenged, are considered to be "disruptive". This paper explores (i) the complex 30-year history of a biotelemetry science "disruption" with the management of Fraser River salmon fisheries, (ii) the transformation of biotelemetry science from a disruptive to an accepted science, and (iii) the circumstances that have now made it one of the most important tools for managing Pacific salmon fisheries. We conclude with an overview of a successful case study involving the co-production of biotelemetry science to inform the management of the British Columbia marine recreational fishery. The approach we advocate for provides a pathway for all telemetry practitioners to avoid potential pitfalls and take advantage of what we have learned to ensure biotelemetry science continues to have the potential to generate relevant knowledge to inform management of all socio-economically important fishes.

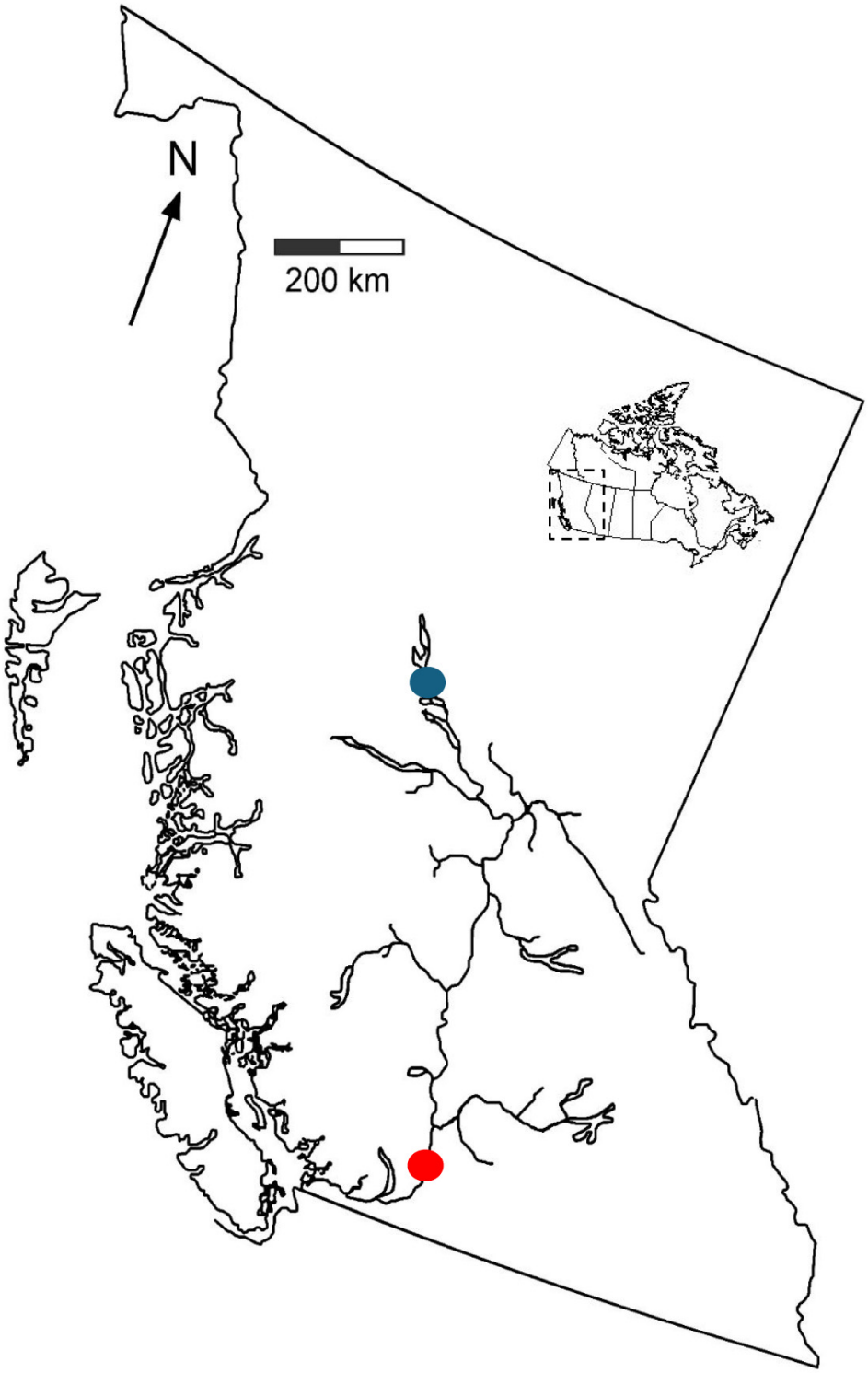
Key words: biotelemetry, decision-making, research co-production, stakeholders, Indigenous, recreational and commercial fisheries

Introduction

In their review of case studies demonstrating strong integration of biotelemetry science into fisheries or habitat management, Brooks et al. (2018) provided a detailed description of how biotelemetry activities informed the management of Fraser River salmon fisheries. While this long-term case study (early 1990s to 2017) was described in impressive detail, it did not discuss "the elephant in the room" which was that serious conflict and controversy surrounded the methods and reliability of biotelemetry science throughout much of that time period, limiting its full management application. Young et al. (2018) argued that aforementioned case study revealed that biotelemetry was a "disruptive science", a novel technology or approach that, if broadly accepted, would require a significant rethink in policy or management practices. Such rethinks are often contested, and certainly have been in the case of biotelemetry science. In a broader sense, a disruptive science challenges collective wisdom and "worldviews" on issues, which can be a deeply uncomfortable process for the people involved in a community of practice, and biotelemetry has had this effect globally (in both aquatic and terrestrial realms; Hussey et al. 2015; Kays et al. 2015). This perspectives paper relies on our 30-year history of using biotelemetry and explores (i) the complex history of the biotelemetry "disruption" with the management of Fraser River salmon fisheries, (ii) the transformation of biotelemetry science into an accepted science, and (iii) the circumstances that have now made it one of the most important tools for science-based management of Pacific salmon fisheries. We conclude with an overview of a successful case study involving the co-production of biotelemetry science that has directly informed the management of the British Columbia (BC) marine recreational fishery.

Biotelemetry involves the electronic tagging and remote tracking of animals within their environments (Cooke et al. 2004) and has become an important research tool in recent decades as the suite of available technologies has expanded and the cost decreased (Hussey et al. 2015). A variety of biotelemetry platforms exist for use in aquatic systems, including radio, acoustic, passive integrated transponder (PIT), and satellite, each with their distinct benefits and limitations (summarized in Cooke et al. 2012). Biotelemetry has opened a portal for understanding the hidden lives of fish (including behavior, survival rates, environmental relations, and migration corridors) in habitats ranging from small streams to entire ocean basins (Matley et al. 2022).

Fig. 1. Map of British Columbia showing the Fraser River mainstem and its major tributaries. Red dot is location of Hells Gate; blue dot is spawning location for Early Stuart sockeye salmon. Inset is a map of Canada with dotted lined around British Columbia. UTM map modified from Hinch and Bratty (2000).



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Large numbers of fisheries and aquatic scientists now use biotelemetry (Hussey et al. 2015), and biotelemetry research networks exist in the United States, Europe, Canada, Australia, South Africa, among other locales (Matley et al. 2022).

Our experiences with utilizing biotelemetry research to address salmon management issues are largely within the Fraser River (Fig. 1), one of Canada's largest rivers that drains ~1/3rd of the province of BC (Dorcey 1991). It is the largest producer of Pacific salmon (*Oncorhynchus* spp.) and one of

Fig. 2. Top left—Hells Gate; bottom left—east bank fishway entrance with three people (SGH in foreground) standing on fishway deck next to a fixed radio tracking antenna with a person holding a mobile antennae (note the 2 m high wall of water pouring around the fishway entrance); top right—electromyogram radio transmitter with its two sensing electrodes that get surgically inserted into the salmon's main swimming muscle, a dime indicates scale; bottom right—extremely fast and turbulent flows immediately adjacent to the fishway entrance. Photo credits—SGH.

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the most intensely fished rivers in Canada. Three fishing sectors target adult migrating Pacific salmon: commercial, recreational, and First Nation (Indigenous), with different catch allocations, restrictions, and often different gear. Regulation of these fisheries is complex, involving Fisheries and Oceans Canada (DFO), the Canada–U.S. Bi-National Pacific Salmon Commission (PSC), and co-management arrangements with First Nation communities and stakeholder groups such as commercial fisheries, recreational fisheries, and conservation groups via advisory board committees that meet regularly with DFO to discuss planning and forecasts, escapement goals, and allocation of harvest (Cohen 2012).

Start of the disruption

In 1990, the Canadian government implemented its "Green Plan", a comprehensive 5-year environmental action program providing $3 billion (CDN) in new funding for over 100 initiatives, which included helping to make fisheries more sustainable and improving the health of the Fraser River (Government of Canada 1990). As a new postdoctoral fellow, SGH led a DFO–University of British Columbia (UBC) collaborative Green Plan project investigating the energetics and up-river passage concerns for Fraser River sockeye salmon (*Oncorhynchus nerka*), the most commercially valuable salmon species and one of the most important fish species to local Indigenous people's food security, spirituality, and ceremony (Jacob et al. 2010). The focus of study was on the first sockeye salmon population of the year to migrate up the Fraser River (Fig. 1). The Early Stuart population travels 1200 km from the ocean to its spawning grounds each July, a period when historically river discharge is extremely high often creating barriers to migration at some river locations, in particular "Hells Gate" where the mainstem is at its narrowest (Fig. 2). In 1913, a landslide occurred here obstructing the upstream migration for numerous populations—30 years later, the USA and Canada partnered on building large fishways to assist up-river migrating salmon (Roos 1991). Today, centre-line water speeds can exceed 10 m/s and this reach can be a region of extreme turbulence and difficult passage despite presence of fishways (Fig. 2). This study was the first ever large-scale biotelemetry study of salmon migration in the Fraser River,

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and the first large-scale application of radio telemetry transmitters equipped with electromyogram sensors. This technology provided direct measures of sockeye swimming speeds (Hinch et al. 1996), which enabled estimates of reach-specific energy use (Hinch and Rand 1998).

During telemetry tracking in 1994, an odd behaviour was observed. During the first 2 weeks of July, tagged sockeye travelled through the Fraser Canyon and toward Hells Gate but during the second 2 weeks, many stopped migrating and some headed back downriver never to be seen again. Clarke et al. (1995) suspected it was related to an unprecedented rapid change in water temperature (first 2-week daily average = 14.2 °C; second 2-week daily average = 19.4 °C with several days >20 °C) (Lauzier et al. 1995). The daily average temperature in July 1993 was approximately 17 °C with no days greater than 19 °C. It would be another 15 years until respirometry experiments on this population revealed that temperatures > 19 °C leads to cardiac and metabolic collapse during up-river migration (Eliason et al. 2011).

By the end of summer 1994, 1.3 M sockeye were estimated to have "disappeared" or went "missing" during their river migration (Fraser 1995). "Missing fish" can arise from a combination of factors including errors in estimating: river entry escapement, spawning ground escapement, or river harvest. It can also arise from river migration mortality or unreported river harvest. SGH's telemetry observations of migration mortality associated with high temperatures supported the former with biotelemetry estimates suggesting that up to half a million sockeye may have died due to temperature-related factors (Clarke et al. 1995). A federal public investigation which involved interviewing numerous private citizens, Indigenous fishers, commercial and recreational fisher stakeholder groups, fisheries managers, and scientists called this estimate "highly speculative", but the investigation also noted that while some unreported harvest likely occurred, it was not at a scale to remove the number of fish that were designated as missing (Fraser 1995). Nevertheless, unreported fishing (termed "illegal" in the report, largely by Indigenous groups), poor management, and poor fish counting technology bore the brunt of the blame (Fraser 1995). It was clear that biotelemetry science did not support the worldview of those in commercial or recreational fishing groups, nor of most fisheries managers.

At a 1995 DFO-sponsored regional conference, SGH reported that over the previous 2 years ~25% of telemetry tracked Early Stuart sockeye had approached the Hells Gate fishway (Fig. 2) but did not pass. A subsequent presenter (a senior DFO engineer responsible for managing the fishways) bluntly stated in his presentation, though with no data to support it that, "all the fish get past Hells Gate!". This was the second time in a year that biotelemetry research results were dismissed by government officials. The electromyogram biotelemetry results eventually revealed a mechanism for passage failure at Hells Gate—fish that swam in a hyperactive way and exhibited extremely fast swim speeds never successfully entered the fishway (Hinch and Bratty 2000; Fig. 3).

Biotelemetry science becomes more disruptive

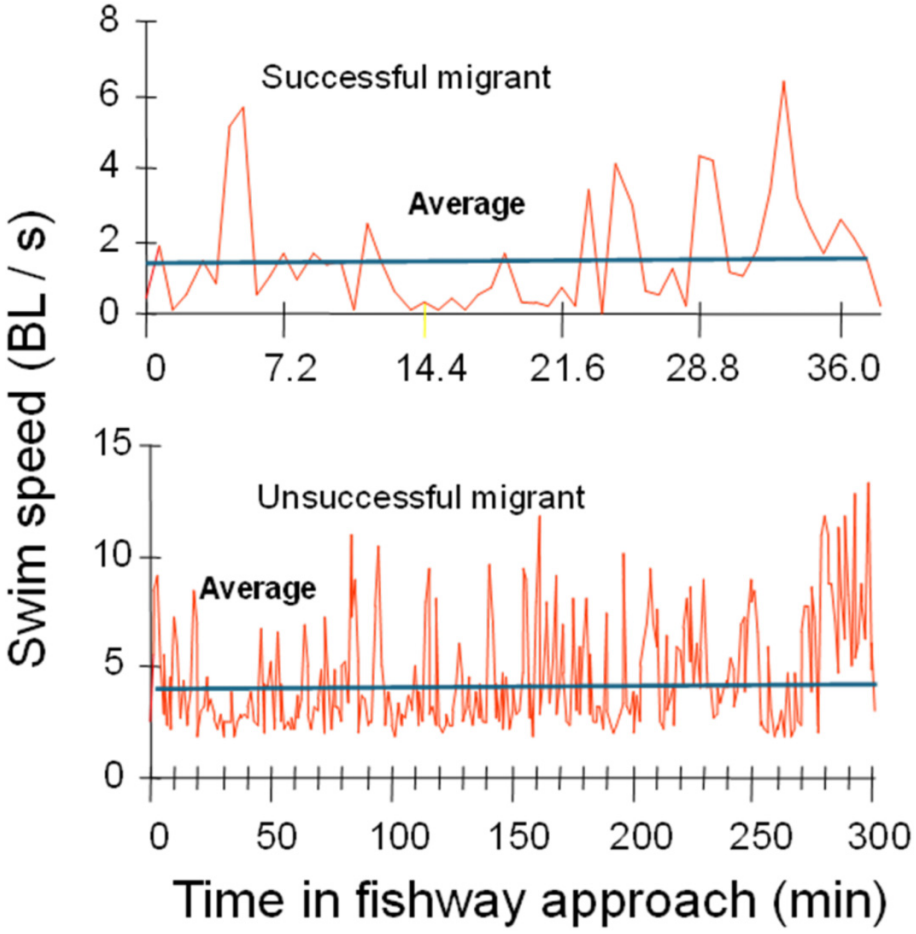
A fascinating biological situation, a vexing management issue, and a conservation crisis were all apt descriptors for a phenomenon that began in 1996 and has continued to the present (Cooke et al. 2011; Hinch et al. 2012). Adult Late-run Fraser River sockeye salmon, the dominant run in some years, and one of the most valuable and important groups of salmon in Canada were unique among sockeye salmon populations anywhere, and perhaps among Pacific salmon in general. Following their directed migration from the ocean they used to "hold" or "delay" in the estuary (i.e., the Strait of Georgia) for several weeks (i.e., 3–6) prior to migrating into the mainstem of the Fraser River and onward to spawning areas. Beginning in 1995, this delay period shortened substantially to 5 days or less. Early migration was associated with "en-route" mortality during upstream migration and "pre-spawning" mortality after arrival at spawning areas. In years of the most extremely early entry (e.g., 2000, 2001), total freshwater mortality exceeded 90% (Hinch and Gardner 2009) (Fig. 4).

In 2002, biotelemetry research involving collaborations among government, private sector, and university groups began exploring this phenomenon (Hinch and Gardner 2009). A large marine receiver network of acoustic receiver lines had recently been installed along coastal BC operated by the Pacific Ocean Shelf Tracking project with the Ocean Tracking Network taking over management of several of these receiver lines in 2008 (Jackson 2011). Radio and acoustic receiver networks were also deployed at numerous locales throughout the Fraser River watershed (Hinch et al. 2012). Overall, this network provided extensive coverage for tracking homeward migrating sockeye salmon from when they made landfall from the open ocean to coastal areas and during their coastal and up-river travel to spawning grounds.

There are 19 major sockeye salmon stocks spawning in the Fraser River watershed, many of which co-migrate in coastal and riverine areas, so to know the intended destination of tagged fish, and hence be able to determine if a fish perished while heading home, we needed to know the stock origin. The advent of molecular approaches to differentiate populations (*aka* genetic stock identification) meant that a small tissue sample taken from a tagged fish could provide that critical information (Beacham et al. 2004). To understand why fish were perishing, not just where, we also needed a mechanistic understanding of individual fish behaviour and survival. To obtain that from tagged fish, we pioneered approaches for blood sampling to examine a range of plasma ions and osmoregulatory indices, as well as energy and metabolism indices like glycogen and lactate, and reproductive and stress hormones (see Cooke et al. 2005). A small tissue biopsy from the first gill arch was used to assess ionoregulatory function and for functional genomics assessments, adipose fin tissue was taken for genetic stock identification, and lipid reserves were assessed by microwave energy meter (Cooke et al. 2005).

In 2004, another management crisis emerged as 1.6 M sockeye (32% of the total run) went "missing" during their up-river migration in the Fraser River (Williams 2005). A large segment of these fish belonged to the Late-runs, but fish had

Fig. 3. Swim speed in body lengths (BL) per second, blue line is the average, estimated from electromyogram transmitter data in relation to the time a fish spent in the downstream approach section of the Hells Gate fishway. Two female sockeye salmon are represented; one entered and passed the fishway (Successful), the other did not enter the fishway (Unsuccessful). Figures modified from Hinch and Bratty (2000).



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disappeared from all run-timing groups. The federal Minister of Fisheries convened a public and independent investigation of this issue. Led by Bryan Williams, a former Minister of Fisheries, his committee comprised representatives of commercial and recreational fisheries organizations, Indigenous and environmental groups, and DFO managers. SGH and SJC made presentations to the committee highlighting our group's biotelemetry research showing that levels of stock-specific disappearances of sockeye could largely be explained by temperature-mediated migration mortality (Fig. 5). Several stakeholders from the commercial and recreational fishing industry who testified and others who were on the committee refused to believe the telemetry results claiming there was no evidence of mass die-offs of fish (e.g., large numbers of visible floating carcasses) which they believed would be evident. This belief was later disproved as moribund migrating salmon often sink and the Fraser River's turbidity would hide most that do not sink (Patterson et al. 2007). Moreover, even with that massive level of mortality, the carcasses could simply be "diluted" by the vast quantity of water that flows down the Fraser every day. There was evidence of unreported and hence unaccounted for harvest, primarily by Indigenous fishers yet it was determined that this harvest did not occur at a large enough scale to account for the massive levels of missing fish (Wappel 2005; Williams 2005). Biotelemetry science had contradicted the world views of many non-Indigenous stakeholders in the fishing industry in how they perceived, and expected to witness, natural salmon mortality as well as the perceptions of unreported harvest by Indigenous groups, and this was prompting a rethink in management. Fisheries stakeholders were experiencing an existential crisis with media coverage of them conducting illegal fisheries with media headlines stating, "I've got nothing to lose." The results of the inquiry not only challenged stakeholder's views on "missing salmon", but because climate change was at the core of river warming as noted at the inquiry, there was a growing realization that their way of life was going to change. Nevertheless, this biotelemetry disruption resulted in the final report concluding that temperature-mediated mortality was only one of several factors contributing to missing fish and not the major factor as the biotelemetry science had indicated (Williams 2005).

Given this was the second time in 10 years that large numbers of sockeye disappeared from the river and most of the

Fig. 4. Percent of total run that died after passing the mission hydroacoustic facility situated 50 km upriver from the ocean, but before reaching spawning grounds in relation to when 50% of the population had passed the hydroacoustic facility. Data are for the Weaver Creek sockeye salmon population, one of several Late-run stocks. Green dots represent years from 1974 to 1994; white and black dots represent years from 1995 to 2008. Black dots provide examples of the total number of fish that died that year during the migration in that one population. Figures modified from Cooke et al. (2004).

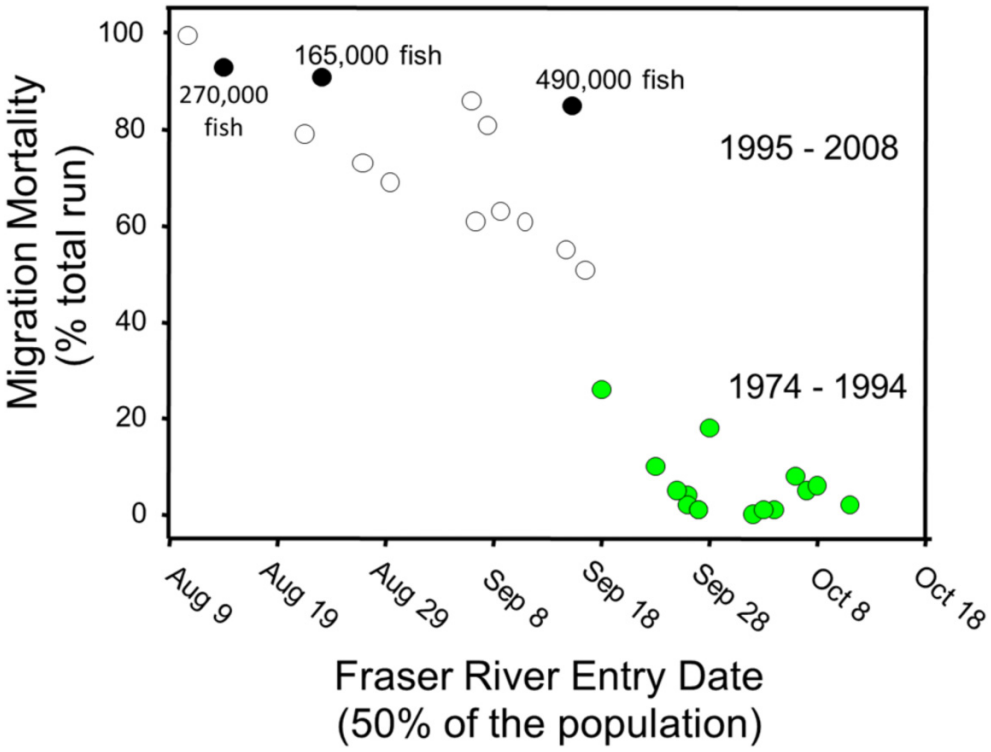
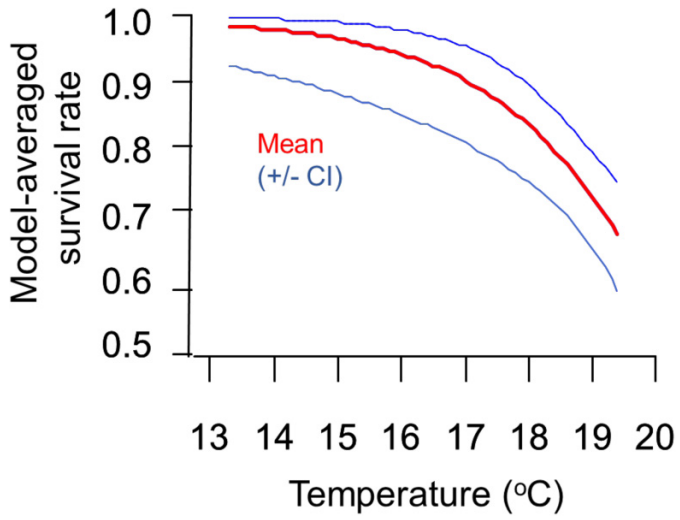


Fig. 5. Proportions of radio tagged sockeye salmon, tagged in the ocean, but assessed for survival once in the Fraser River. Survival was based on fish reaching natal spawning regions in relation to average encountered river temperature. This figure is just for the Shuswap population, one of the largest Late-run stocks. Different stocks have different shaped curves, but all show a steep decline after 18–19 °C. There were not enough fish surviving at temperatures > 19.5 °C to include in the models. Figures adapted and modified from Martins et al. (2011).



blame was being directed to unreported harvest by Indigenous fishers, Nguyen et al. (2016) interviewed over 400 Indigenous and recreational fishers to understand their perceptions of threat to their fisheries. Not surprisingly, the threat was far stronger among recreational fishers, who were highly critical of both Indigenous and commercial fishers resulting from complaints about fairness as Indigenous fishers had priority access to salmon (affirmed by the Supreme Court's 1990 Sparrow decision), and commercial fishers were accessing salmon largely in the ocean before anglers have access in the river. In contrast, Indigenous complaints were more directed at the federal government in terms of the blame they were bearing for missing fish and fisheries mismanagement in general. Nguyen et al. (2016) found that environmental change was exacerbating these conflicts. Interestingly, our biotelemetry results supported both groups' perspectives as we determined Indigenous groups were not primarily to blame for missing fish in the Fraser River and that many salmon were in fact dying in the ocean before anglers would ever have access to them (Cooke et al. 2006*a*, 2006*b*).

The advent of conservation physiology with salmon

The incorporation of biopsy and bioassay assessments with biotelemetry revealed for the first time, with any anadromous migratory fish, key physiological factors affecting ma-

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rine migration success, failure, and river entry timing (Hinch et al. 2006). Specifically, sockeye salmon that failed to enter the river from the ocean exhibited indicators of elevated anaerobiosis and stress (e.g., elevated plasma lactate, glucose, and cortisol) (Cooke et al. 2006*a*, 2006*b*; Crossin et al. 2007) and fish that migrated into the river weeks earlier than usual had depressed energy states and advanced reproductive state (Cooke et al. 2008; Crossin et al. 2009*a*, 2009*b*). The fact that these latter issues were observed in fish that were tagged weeks before reaching the Fraser River mouth suggested the genesis of the early migration phenomena was likely in the open ocean and not in the adult coastal migration region (Hinch et al. 2012). The factors affecting riverine migration success also had strong physiological links. Fish tagged in the ocean that died in the lower Fraser River had high plasma osmolality (Cooke et al. 2006*a*, 2006*b*; Cooperman et al. 2010), whereas fish tagged in the ocean that died in the upper reaches near spawning regions had low reproductive hormone levels (Cooke et al. 2006*a*, 2006*b*). Sockeye salmon that were tagged near spawning regions and died prior to completing the migration had low energy, high plasma osmolality, and blood-clotting issues (Young et al. 2006). Using the first ever 40K gene microarray designed for fish, Miller et al. (2011) identified a genomic signature (involved ~1000 genes) in ocean tagged fish associated with a 13.5-fold greater chance of dying during the spawning migration, possibly related to a novel virus. Fish that died during the homeward migration had problems with metabolic processes, osmoregulation, and maturation.

High temperature and sockeye mortality

Using data from 1000s of tagged fish, Martins et al. (2011) used sophisticated statistical models to demonstrate that sockeye riverine migration survival was strongly related to river temperature (Fig. 5) in a stock-specific fashion with some stocks having higher thermal resilience than others. This stock-specific finding was supported by swim tunnel respirometry studies showing Summer-run stocks having higher metabolic optimal and critical (e.g., lethal) temperature values compared to Late-run stocks (Farrell et al. 2008; Eliason et al. 2011) presumably arising from adaptations to historical migratory thermal conditions. Respirometry also revealed that there was only a 3–4 °C difference between optimal and critical temperatures, driving home the importance of how even small levels of riverine warming can contribute to elevated migration mortality (Fig. 5).

Crossin et al. (2008) conducted the first ever temperature manipulation experiment with migrating adult salmon using biotelemetry wherein they exposed normal-timed Late-run sockeye salmon to either 10 or 18 °C for over 3 weeks in a lab, then tagged and released them to complete their spawning migration. In only a 12 km route, mortality of 18 °C treated fish was 60%, twice that of the 10 °C treated fish. Gill biopsy at time of release revealed much higher levels of *Parvicapsula minibicornis* infection, a naturally occurring myxosporean parasite which proliferates in warm temperatures and is known to cause mortality when river temperatures exceed 18 °C (Wagner et al. 2005).

After conducting 6 years of physiological biotelemetry research on migrating Fraser River sockeye salmon, the three fundamental findings relevant to fisheries management were that: (1) high temperatures kill river migrating salmon in a stock-specific fashion; (2) high temperatures kill even more salmon if they were in poor physiological condition at start of river migration, and (3) abnormally early migrating salmon were not only physiologically ill-prepared for freshwater entry, their behaviour placed them in river temperatures up to 6 °C above their tolerance range which killed them at extremely high levels (Hinch et al. 2012).

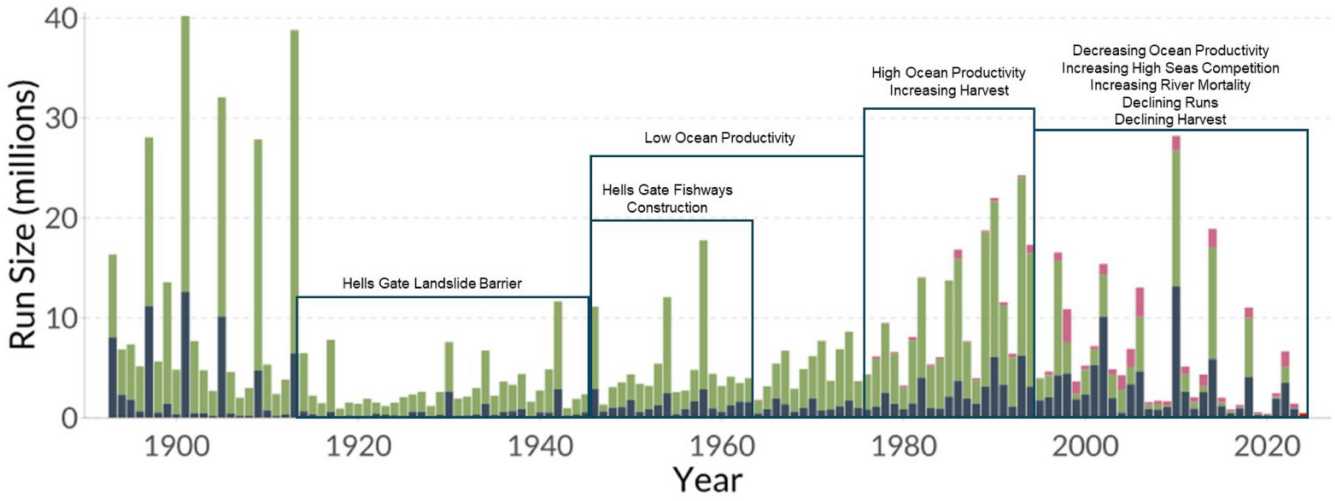
Biotelemetry science continued to disrupt

In 2008, SGH organized the "Conference on Early Migration and High Mortality in Sockeye Salmon" inviting over 70 government fisheries managers and scientists, fisheries consultants, Indigenous representatives, and academics to hear detailed presentations from academic, government, and consulting groups on research results from the previous 5 years on the high mortality issues and discuss how this science might get incorporated into management decisions (Hinch and Gardner 2009). Overwhelming research showed that in-river mortality was caused by high temperatures, killing fish in a stock-specific thermal fashion. Yet, several fisheries managers were skeptical and could not be convinced on how to use the synthesized biotelemetry knowledge which was backed by scientific consensus. One manager stated, "to start applying some of these results, we will need more years, more data and more certainty" (Hinch and Gardner 2009).

Managers wanted migration-based harvest and natural mortality models that show consistent predictability each year—yet in an era of changing climates, this will be extremely difficult with new phenomena seemingly affecting salmon each year (increasing river temperatures making disease more prevalent, changes to ocean currents and productivity, changes in predators' distribution and abundance) (Hinch and Gardner 2009). Further, some managers questioned the validity of the biotelemetry results with comments like, "Was there any evidence that fish were being mishandled enough during sampling to cause a lot of mortality? How many of the fish that disappeared are [researchers] responsible for? Could the biopsies have contributed to mortality? Were survival rates corrected for tag failure?" (Hinch and Gardner 2009). While being legitimate concerns, these comments further confirmed the reticence of incorporating biotelemetry science into management, leading one of the academic scientists, world-renowned fish physiologist Dr. Tony Farrell (Professor at UBC), to loudly exclaim at one point "It's temperature, it's temperature, it's temperature!!"

A management decision to increase the in-river harvest of sockeye before mid-August thus targeting the earliest of the Late-runs, which biotelemetry results showed are going to die enroute anyway, was considered but dismissed due to potential bycatch of Summer-run sockeye and other endangered stocks (Hinch and Gardner 2009). Ultimately, managers decided their only risk-averse option was to restrict harvest as much as possible on early migrating Late-runs despite knowing they were going to perish before spawning. This early-

Fig. 6. Total run size of Fraser River sockeye salmon from 1893 to 2024. Green bars are total harvest, blue bars are spawning escapement, and red bars are "missing fish" which generally reflects enroute river mortality. Key factors affecting trends are indicated on the graph. The effects of the Hells Gate landslide on returning adults were evident by 1918 a few years after the landslide, some sockeye populations spawn downstream of this location so not all were impacted. The construction of several fishways at Hells Gate occurred over several years during the same time that the Pacific decadal oscillation (PDO) was in a "negative phase" meaning general upwelling of nutrients and associated food production for ocean rearing sockeye was low. This resulted in relatively reduced returns despite enhanced passage at Hells Gate. In 1976, the PDO shifted to a "positive phase" which led to enhanced survival of ocean rearing sockeye, leading to high returns. During the 1980s and early 1990s, ocean densities of salmon were increasing from enormous salmon hatchery programs in Alaska, Japan, and Russia as well as enhanced survival of wild populations due to favourable ocean food conditions. Several factors changed starting in the early 1990s including rising sea surface and river temperatures due to climate change, record high abundances of sockeye, pink and chum salmon in the north Pacific Ocean, and by early 2000s a shift back to a negative PDO. While there were a few years of reasonably high returns during this last time period, these factors generally caused large declines in returning Fraser River sockeye, high levels of enroute river mortality, the near elimination of fisheries, and some stock collapses. Citations: Roos (1991); Mantua and Hare (2002); Martins et al. (2012); Connors et al. (2020, 2025). Figures obtained and modified from Pacific Salmon Commission (2025; www.psc.org; June 1, 2025 retrieved).



entry behavior created a major conservation issue for Late-run stocks and resulted in severe constraints on harvest with enormous economic and social implications.

Biotelemetry science is finally embraced by fisheries managers and the courts

By 2009, Fraser River sockeye returns had been declining for nearly a decade and the high catches of the 1980s and early 1990s were gone (Fig. 6) as were the livelihoods of many commercial fishers and food security for indigenous groups. As a result, the Prime Minister of Canada established a Federal Judicial Inquiry (aka The Cohen Commission) to examine the science, management, policy issues contributing to declining productivity and spawning abundance in Fraser River sockeye salmon. The inquiry was conducted in a federal court involving dozens of lawyers, submission of 1000s of pieces of evidence, and depositions and testimonies of numerous expert witnesses. It was highly contentious and adversarial (Cohen 2012). Some of the key biological issues that the inquiry examined included the broad impacts of annual increases in summer river temperatures on migration and spawning success (Fig. 7). The ocean was becoming less productive while salmon density and competition was increasing in rearing areas of the North Pacific due to changing prey levels, warming temperatures, and increasing hatchery production from Alaska, Russia, and Japan (Fig. 6; Cohen 2012; Conners et al. 2020, 2025). The Atlantic salmon industrial pen-culture industry was expanding in coastal BC with significant concerns about pathogen and disease transfer to wild Pacific salmon (Cohen 2012). And as noted above, some of the largest runs of Fraser sockeye had been migrating into the river weeks earlier than usual, associated with extreme mortality occurring in river (Hinch et al. 2012). SGH provided court room testimony, analyses, reports, and scientific papers focused on biotelemetry-based science. In his final report, Judge Cohen acknowledged that the data were overwhelming that high water temperatures were a major factor in the in-river mortality of sockeye salmon (Cohen 2012).

Two federal inquiries, the incorporation of biopsy and bioassay with biotelemetry, and thousands of tagged and tracked sockeye later, managers broadly embraced biotelemetry science. They started using it along with climate forecasting models to predict stock-specific levels of migration mortality which was being used to inform harvest decisions. In some years (e.g., 2013 and 2018), river migration mortality was anticipated pre-season to be 70%–80% based on fisheries managers understanding from biotelemetry

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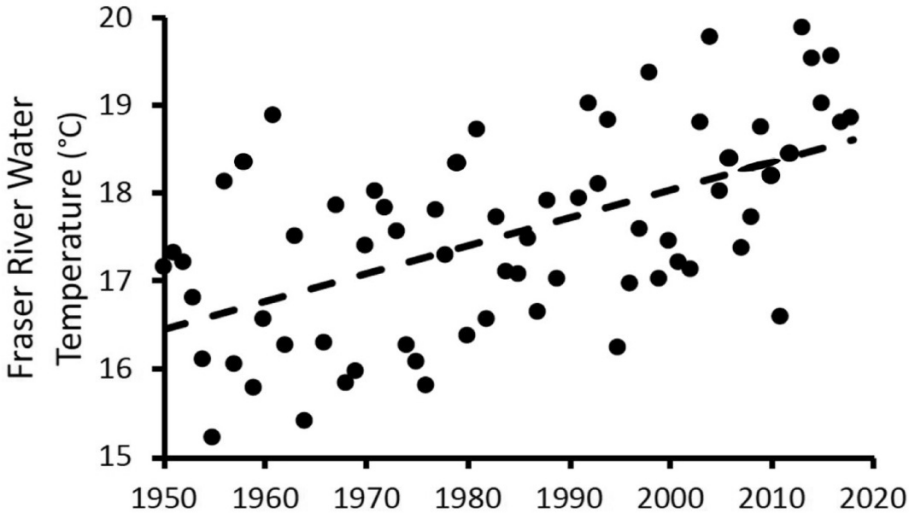
Fig. 7. Mean daily Fraser River water temperature during August measured in the lower Fraser River, black dots are years 1950–2018. As these are means, since 2000 on some days, temperatures would have exceeded 21 °C which can be lethal to migrating sockeye salmon. The dashed line is the linear regression explaining over 30% of variation in river temperatures. River is warming at 0.3 °C per decade. Figures adapted and modified from Lapointe et al. (2020).



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results and river thermal-hydrology modelling. This meant they were able to reduce or completely stop fisheries in the ocean to ensure spawning ground escapement targets could be reached because large levels of natural mortality were expected in the river. The chief biologist of the PSC noted that to get "buy-in" from fisheries stakeholders to "accept" the need to close fisheries, he would rely on the mechanistic biotelemetry findings to explain the closure decisions (Mike Lapointe 2008, personal communication). However, stakeholder acceptance of biotelemetry science was also being assisted simultaneously through an annual event held at UBC ("Symposium on Pacific Salmon Migrations" now coming into its 20th year) which brings together ~60–90 people involved with management of salmon habitat or fisheries from indigenous groups, NGOs, municipalities, provincial and federal agencies, and academia. Organized by SGH, it involves presentations primarily by graduate students who conducted recent research with relevance to management, policy, or extension objectives pertinent to those in attendance. All participants "park" their affiliations at the door and discuss the research results with an eye on providing feedback to trainees on how results apply to their groups, and how research could be expanded to assist their groups. The original intent of the symposium was to provide a learning and extension opportunity for graduate students. However, it unexpectedly served an equally, and potentially more important function, which was to bring stakeholders and others into the "biotelemetry tent".

Still, some stakeholders remained suspicious of fisheries decisions being informed by biotelemetry science (Young et al. 2016). In 2009, we collaborated with DFO, a private consulting company, and recreational angler and Indigenous fishing groups to use radio telemetry to determine survival to spawning regions of sockeye salmon captured and released in the lower Fraser River using beach seines and rod and reel gear. The angler stakeholders were concerned of potential effects of telemetry on fish survival so required us to include a riverbank "holding" study wherein some angled fish were held for 24 h observations prior to release so that "tagging" effects could be assessed. Upon release, the net-pen held fish had extremely high plasma cortisol and glucose relative to those immediately released from capture, and only 3% of these fish reached natal areas compared to 36%–52% of the biopsy sampled immediately released fish (Donaldson et al. 2011). This was the opposite finding that the stakeholders had anticipated given their worldview on biotelemetry! Nevertheless, we always took biotelemetry concerns seriously when raised by managers and stakeholders and conducted validations whenever possible to ensure that we fully understood the consequences of tagging and related procedures on fish. Those learnings further refined our methods and also provided clarity around uncertainties (Cooke et al. 2005, 2012).

Ending the disruption

Over the past 20 years, DFO's Integrated Harvest Planning Committee brings together First Nations, commercial and recreational harvesters, and environmental interests to review and coordinate fishing plans, and resolve potential issues among sectors (DFO 2025*a*). However, as we have witnessed with the incorporation of biotelemetry science into management, conflict persists between managers and stakeholders. Young et al. (2016) interviewed people involved with salmon management or harvest about how they react to, and utilize, new knowledge involved with the salmon fishery. They discovered that conflicts between managers and stakeholders may be explained by how these groups differ in their "knowledge mobilization". Government employees (federal managers and scientists) prefer knowledge that is problem-oriented, quantitative, and stripped of unnecessary

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interpretation, which seems to be a technocratic approach to depoliticize knowledge and avoid conflicts. Stakeholders (which included fishers, Indigenous rightsholders, and environmental groups) prefer knowledge that reflects experiences and contextual social-ecological knowledge of their groups. They want information and interpretation in the form of words and stories not scientific papers; they prefer information via in-person communication, regulation handbooks, media, and the Internet (Nguyen et al. 2012). Most importantly, the knowledge provider needs to have built trust with stakeholders, and this issue is as important as the knowledge itself (Young et al. 2016).

In a "co-management" world, stakeholders and agencies are now supposed to work together yet stakeholders employ different criteria for evaluating the value and utility of science than do government scientists and managers. Biotelemetry science revealed the need for large changes to Pacific salmon management and policy that were not necessarily appreciated or understood by those affected by the management or policy (Young et al. 2018). It is this type of "disruption" that prompts authorities to ignore or underplay biotelemetry findings and data. For example, the conclusions of the Williams Inquiry where biotelemetry had clearly demonstrated that large levels of migration mortality could be explained by high temperatures, yet unreported harvest by Indigenous groups was given as much credence as an explanation for missing fish because this fit the world view of many non-Indigenous fishers and politicians (Wappel 2005; Williams 2005). Young et al. (2018) noted that governance involves fundamentally different norms and processes than scientific research and despite biotelemetry science continuing to be viewed favorably as a source of new knowledge, it continued to lack practical value to those in "co-management" situations.

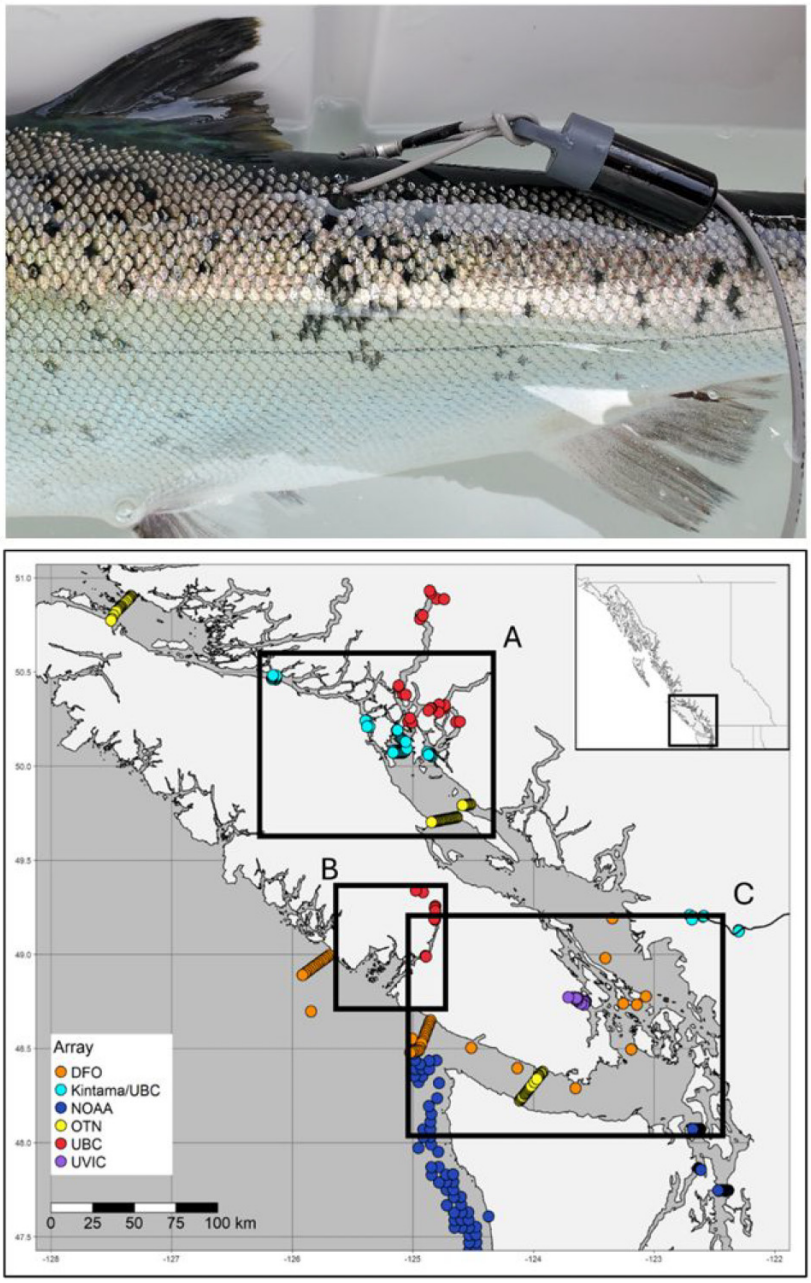
Large numbers of fisheries and aquatic scientists use biotelemetry (Hussey et al. 2015) and biotelemetry research networks now exist around the globe (Matley et al. 2022). Other than the physiological biotelemetry sockeye salmon research in the Fraser River discussed in this paper, there are only a few examples of biotelemetry findings and data being directly integrated into evidence-based fisheries management (Cooke et al. 2021; although see Klinard et al. 2025). To examine why this was the case, Nguyen et al. (2018) surveyed >200 global fish biotelemetry experts (academic, government, stakeholders, NGOs). The primary finding was that lack of management integration of telemetry-derived knowledge was due to inflexible, nonadaptive, stagnant governance and institutional cultures. Young et al. (2014) noted that DFO implicitly endorses a dysfunctional "pipeline model" of information exchange by conceptualizing "peer-reviewed science" as a collection of facts, divorced from their producers, to be consulted on an as needed basis. To change this, personal relationships and engagement between researchers and stakeholders was needed (Young et al. 2016; Nguyen et al. 2018). "Relationships" were important for designing relevant research questions and to improve transparency, legitimacy, and credibility of telemetry results which will facilitate their utilization (Nguyen et al. 2012, 2018). Recently, Klinard et al. (2025) in a large review of telemetry-based research in the Great Lakes identified many similar barriers as we report to the integration of telemetry findings into management which included among other things, communication and accessibility of results, institution and stakeholder perceptions and uptake of results, and alignment with management priorities.

Biotelemetry science and fisheries stakeholders: case study of the BC recreational salmon fishery

As we entered the 2020s, sockeye salmon populations in BC were at their nadir (Fig. 6), fisheries were collapsing, dozens of salmon populations, including the Early Stuart stock and numerous Chinook and coho stocks were designated as endangered or threatened (COSEWIC 2016, 2018, 2020). DFO launched several strategic initiatives to modernize hatcheries, transform harvest approaches, improve understanding of salmon ecosystems, and promote and fund research partnerships. In need of transformational change was BC's most important fishery—the marine recreational fishery. Each year over 220 000 individual licenses are sold (DFO 2025*b*) and the fishery contributes $266 M to the provincial GDP and employs over 5400 people (DFO 2025*c*). DFO's "Selective Fishing" policy requires the live release all nontarget or undersized target fish (DFO 2001). Further, to enable increased access to fishing opportunities while protecting declining populations, "Mark-Selective Fisheries" (MSFs) are increasingly being used wherein all wild fish are released but hatchery fish (identified by a missing adipose fin) can be retained (Rechisky et al. 2024). In the south coast of BC in 2024, almost twice as many coho and Chinook salmon were released (408 540) as were kept (219 152) (DFO 2024). If release mortality of wild fish is high, this could have devastating effects on wild stocks.

The success of MSF and capture and release in general as management tactics are inherently dependent on an understanding of how much mortality is experienced by released fish and the assurance that it can be kept relatively low. DFO currently assumes 10% release mortality (DFO 2025*d*), a level derived from old and flawed science (Hinch et al. 2024; Lunzmann-Cooke et al. 2024). There was an urgent need to examine levels of capture and release mortality and determine ways to minimize it through the development of best practices. To address this, we led a large-scale, acoustic biotelemetry focused research program (Fig. 8). Because the results would have direct impacts on harvest management and salmon conservation, the potential for serious disruption, conflict, and controversy was high. Given the recommendations from our biotelemetry social science studies (Nguyen et al. 2012, 2018; Young et al. 2014, 2016, 2018), SGH created and chaired a project steering committee with ~20 representatives from government (scientists and managers), and advocates from the sports fishing industry and salmon conservation NGOs—this committee reflected the breadth of stakeholders in the marine recreational fishery. The committee regularly advised the investigators on refining research questions and helped navigate the core management concerns of both the fishing and conservation sectors.

Fig. 8. Bottom figure is map of southwest coast of British Columbia with Vancouver Island as the main landmass in the centre. The Fraser River is near the "C". The lettered boxes reflect three different acoustic telemetry tracking areas as part of the University of British Columbia (UBC) led capture and release program. Inset map shows study location in the province. The coloured dots represent individual acoustic sea-bed receivers maintained by several collaborating organizations (DFO, Kintama Research Services, UBC, US National Oceanographic and Atmospheric Administration (NOAA), Ocean Tracking Network (OTN), and the University of Victoria (UVIC)). The top figure is a photo showing the location of an external acoustic tag on a Pacific salmon. Photo credit—SGH.



Our primary industry partner, the Sports Fishing Institute (SFI) of BC is an NGO dedicated to promoting, enhancing, and protecting sustainable sport fishing opportunities in BC advocating for fishing lodges, resorts, angling guides, hotels, charter operators, boat and tackle manufacturers, insurance organizations, airlines, and individual anglers. Our primary conservation partner, the Pacific Salmon Foundation, is an NGO dedicated to creating healthy, sustainable, and naturally diverse populations of Pacific salmon for the benefit of ecosystems and people advocating for First Nations, Government, other NGO partners, industry, and all salmon supporters. The SFI directly collaborated with us in the field helping to manage logistics, providing vessels, and field assistance. They experienced the biotelemetry method and all the scientific approaches firsthand and came to understand conservation physiology and its potential roles in salmon

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management. We also partnered with them to conduct laboratory studies to complement the telemetry ones—a very powerful approach to better understand the physiological aspects of capture and release, and to address stakeholder and manager concerns over tagging effects. Through these processes, trust developed between the SFI and UBC scientists.

Before any field work was conducted, we developed an outreach and communication plan which included direct interviews with anglers revealing they were keen for new information on best practices to improve survival of released fish and all supported the creation of more educational resources using our study results (Lunzmann-Cooke 2025). With the SFI, we developed an online survey for anglers linked with their "FishingBC smartphone application", a phone app that supports one's fishing license. The app data revealed that our experimental approaches in how we varied the fishing and release experience reflected what was occurring in the fishery (Hinch et al. 2024), and this activity also raised awareness among the angling community of our research by involving them in citizen science (>3000 responses over 3 years).

Our communication strategy also involved the graduate student and postdoctoral researchers presenting their results annually at the DFO harvest planning meetings (e.g., DFO 2025*d*), and we enlisted a well-known recreational angler social media influencer to attend our annual symposia and come to the field to make videos which he posted on his platform. "Fishing with Rod" is one of the most watched salmon fishing YouTube channels in BC with >80K subscribers (Fishing with Rod 2024).

Our 6-year study found that Chinook salmon released with injuries to fins and scales or bleeding, and were brought onboard prior to release, had 15%–20% poorer survival within the first 10 days of release compared to fish in good physical condition, typically those not brought on board and had few injuries, when released (Hinch et al. 2024). A finding corroborated in the laboratory study. Chinook with any type of eye injury had an additional 15%–25% mortality after 50–60 days post-release compared with fish released in good condition. Mortality levels were approximately twice as high for coho salmon (Lunzmann-Cooke et al. 2024) as they were for Chinook salmon. Smaller fish had much higher post-release mortality than larger fish in both species, and high ocean temperatures elevated release mortality rates (Hinch et al. 2024). These results revealed that DFO was seriously underestimating levels of release mortality and that improved capture and release approaches were clearly needed to ensure sustainability of these fisheries.

Co-production of biotelemetry science for salmon fisheries management

We generated 15 best practice recommendations for anglers and DFO to adopt involving changes to gear choice, landing approaches, handling approaches, release approaches, fishing location, and capture rate decisions (Hinch et al. 2024; Lunzmann-Cooke et al. 2024). Our recommendations were embraced by DFO managers and the stakeholders. Our industry partner and our conservation partner separately created online materials for their websites and notified their members and constituents of these important recommendations (Pacific Salmon Foundation 2024) including demonstrating these practices with online videos (Sport Fishing Institute of British Columbia 2024). DFO has started to implement these practices in their communication networks and are considering appropriate regulatory changes. Outreach also included press releases associated with the best practice recommendations, as our earlier studies indicated the print and online media were important sources of information for anglers (Nguyen et al. 2012). This resulted in nearly 200 print and online articles being published globally with 10 live national and regional TV and radio interviews. The total unique visitors per month (UVM—number of distinct individuals who visit a website or digital platform) was >155 M which is considered very good for a story related to fisheries management (UBC Department of Media Relations 2024, personal communication), therefore, the public was likely broadly well-informed.

Around the same time of our capture and release research, other groups were initiating co-produced physiological-based tracking projects to inform salmon management including the "Follow the Fish Program", an integrated Chinook salmon assessment and monitoring study for the west coast of Vancouver Island led by DFO but including numerous collaborator indigenous and stakeholder groups (DFO 2025*e*). This program is using coded wire tags and PIT technologies to follow fish through their entire life, combining physiological stock-specific fish health (genomics) and condition (diet) indices linked to environmental factors (food, eDNA) identifying key biological issues limiting productivity of Chinook salmon. The "Bottlenecks to Survival Program" is an NGO led (Pacific Salmon Commission/British Columbia Conservation Foundation) project in partnership with DFO, Indigenous groups and stakeholders. It examines survival of wild and hatchery Chinook, coho, and steelhead salmon on the east coast of Vancouver Island where physiological and molecular approaches are linked to the tracking of juveniles (~250 000 PIT tags deployed) and sub-adults (hundreds of acoustic tags deployed) identifying survival bottlenecks for wild and hatchery fish, including conducting adaptive management experiments to improve hatchery performance (Pacific Salmon Foundation 2025).

Lessons for future applied biotelemetry research

Biotelemetry was a disruptive science for Pacific salmon as results often flew in the face of collective wisdom and the world views of those in management or stakeholders and others that harvested salmon, and it forced changes in policy and management. While biotelemetry continues to shape our world view on fisheries issues—it will no longer be a "disruptive science" if we can learn from past experiences to help managers and stakeholders integrate biotelemetry further into their perceptions of the fishery and their decision-making processes. Spending face-to-face time with managers and stakeholders fosters mutual respect and trust. Collaborations and relationship building with stakeholders and grassroots community and Indigenous organizations can also put

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pressure on governing bodies via bottom-up pressure. More formal collaborations can blossom from informal relationships (Cooke et al. 2025). In their review of case studies in the Great Lakes on lake sturgeon (*Acipenser fulvescens*), walleye (*Sander vitreus*), and sea lamprey (*Petromyzon marinus*), Klinard et al. (2025) highlighted how biotelemetry has informed aspects of the management of these species. They concluded that collaboration between researchers and managers, facilitated by consistent opportunities for stakeholder engagement, and development of research–practitioner networks, stood out as the most effective means of integrating telemetry into management. Our experiences with using telemetry to help with management of Pacific salmon in the Fraser River led us to similar conclusions.

We have made remarkable advances in fisheries genetics, genomics, and health diagnostics, but alone, they are not enough to provide the dynamic spatial nor causative information needed to manage fisheries. Moving forward, biotelemetry practitioners need to integrate telemetry with physiological and molecular sciences, understand the social and human dimension and communication issues associated with stakeholders and others, and most importantly, coproduce biotelemetry research so that results will be more rapidly and broadly accepted (Cooke et al. 2025). We acknowledge that our experiences, and challenges, with incorporating the use of biotelemetry into fisheries management may not necessarily be the experiences of everyone, and others may have found a "smoother" use, and more rapid uptake of, biotelemetry results into fisheries management activities. Specifically, this may be the experience of some who have more recently incorporated the use of biotelemetry as our experience with the "disruption" began over 30 years ago.

Nevertheless, to those beginning to use biotelemetry to inform fisheries management, or those who are struggling to achieve this with on-going biotelemetry, we recommend you: embrace new biotelemetry technologies even if they might initially appear to be disruptive, become experts in the technology, do the necessary validation studies, create a big tent with your relevant stakeholders and Indigenous groups, coproduce the research which will inform management, bring your stakeholders and managers to the field with you, conduct laboratory studies to complement the telemetry field studies, build mutual trust with stakeholders and Indigenous groups, and communicate results broadly and frequently using media approaches appropriate for managers and all partners.

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Data availability

There are no original data or any code used in this paper. Thus, there is no "Data and Code Availability" to acknowledge in this paper.

Author information

Author ORCIDs

Scott G. Hinch https://orcid.org/0009-0004-2809-734X

Author contributions

Conceptualization: SGH, SJC, NY

Data curation: SGH
Formal analysis: SGH, NY
Funding acquisition: SGH
Investigation: SGH, SJC, NY
Methodology: SGH, SJC, NY
Project administration: SGH
Resources: SGH, SJC
Supervision: NY
Writing – original draft: SGH, SJC, NY
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