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Ancient fish weir technology for modern stewardship: lessons from community-based salmon monitoring

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ABSTRACT

Introduction: The UN Declaration on the Rights of Indigenous Peoples states that indigenous people have a fundamental right to contribute to the management of the resources that support their livelihoods. Salmon are vital to the economy and culture of First Nations in coastal British Columbia, Canada. In this region, traditional systems of management including weirs – fences built across rivers to selectively harvest salmon – supported sustainable fisheries for millennia. In the late-19th century traditional fishing practices were banned as colonial governments consolidated control over salmon.

Outcomes: In collaboration with the Heiltsuk First Nation we revived the practice of weir building in the Koeye River. Over the first four years of the project we tagged 1,226 sockeye, and counted 8,036 fish during fall stream walks. We used a mark-recapture model which accounted for both pre-spawn mortality due to variation in temperature, and tag loss, to produce the first mark-resight estimates of sockeye abundance in the watershed (4,600 – 15,000 escapement).

Discussion: High river temperatures are associated with increased en route morality in migrating adult sockeye. We estimated pre-spawn mortality ranged from 8 – 72% across the four years of study, highlighting the degree to which climate conditions may dictate future viability in sockeye salmon populations. These results demonstrate the power of fusing traditional knowledge and management systems with contemporary scientific approaches in developing local monitoring.

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Introduction

Globally, more than 20 million people – nearly 50% of all fishers – work in small-scale fisheries (Teh and Sumaila 2013), and these fisheries play a key role in poverty alleviation and food security (FAO 2005). Despite their importance for the well-being of coastal communities, science has been slow in developing management and monitoring strategies catered to these smaller-scale fisheries, focusing instead on large, economically valuable fisheries which dominate global catch (Andrew et al. 2007). Most fisheries management is data intensive, depending on centralized data collection and management, which are costly and ill-suited for small-scale or subsistence fisheries (Berkes 2003). In the absence of evaluation and management, many small-scale fisheries around the globe are depressed due to overfishing, limiting their ability to provide benefits to fisheries-dependent communities (Costello et al. 2012). There is a critical need for the development of management approaches which recognize the interdisciplinary complexity of managing small-scale fisheries, building capacity for locally responsive management that does not hinge on centralized management authority and stock-assessment expertise (Berkes 2003; Andrew et al. 2007).

Traditional ecological knowledge and resilient systems of local management have been essential to the survival of aboriginal societies (Johannes 1978; Trosper 2002; Groesbeck et al. 2014); however, local management ethics and practices have been undermined by colonial governments and the influence of globalization (Johannes 1978; Harris 2001). Further, the loss of traditional management systems and fishing practices can lead to social-ecological traps, whereby ecosystems and social institutions undergo lasting shifts toward conditions that provide fewer sustainable benefits to communities (Cinner 2011). In recent times, there has been increasing focus on the benefits of local management and conservation; strengthening local management and monitoring capacity are essential prerequisites to management at the local level (Berkes 2003; Garcia and Lescuyer 2008). While scientists and conservation policy makers increasingly recognize the importance of engaging local communities in monitoring initiatives (Adams et al. 2014), efforts at local monitoring and management have met with mixed

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success (Garcia and Lescuyer 2008). This is particularly true when programs are prescriptive in nature and do not adequately involve community members in development and planning (Adams et al. 2014). Thus, successful local monitoring should be developed in close partnership with community members, be rooted in existing traditions of management, include a strong education and outreach component, and work to build capacity for ongoing monitoring and implementation.

In British Columbia, Canada, First Nations people have harvested salmon for millennia and fisheries remain a backbone of local economies and culture. Prior to the colonial period, indigenous communities developed highly successful management based on traditional laws and practices (Harris 2001; Trosper 2002). In much of British Columbia, these systems of management persisted into the nineteenth century until colonial governments passed laws to prohibit First Nations fisheries and consolidate control of salmon resources (Newell 1993; Harris 2001). In recent years, there has been growing legal and societal recognition of the rights and title of First Nations over the lands within their traditional territories. In 1990, a unanimous decision by the Supreme Court of Canada in the case of Regina v. Sparrow ruled that Section 35(1) of the constitution act guaranteed the right of aboriginals to fish, and a series of legal decisions have subsequently strengthened aboriginal title and rights. On a global scale, the UN Declaration on the Rights of Indigenous Peoples (2007) affirms the rights of indigenous peoples to comanage their natural resources. While comanagement remains a work in progress (e.g., Natcher and Davis 2007), First Nations are working to build management capacity and conduct stewardship that reflects the needs and interests of their communities. There is therefore a critical need for research and monitoring that builds capacity and supports management that fosters long-term sustainability of food, social, and ceremonial (FSC) fisheries.

Fish weirs were used for thousands of years among First Nations in the Pacific Northwest as a means of selectively harvesting returning salmon (Moss and Erlandson 1998). Stone fish traps were also commonly used as recently as the 1950s and remain partially intact in many locations throughout the Central Coast of British Columbia (White 2011). Both technologies provided a foundation for adaptive management, as fishers could evaluate the strength of salmon returns and adjust harvest accordingly (Harris 2001). However, the use of fish weirs and traps was discouraged and ultimately banned during the late nineteenth century, as the colonial government sought to promote and develop the commercial fishing sector (Newell 1993; Harris 2001). Weirs are still routinely used for population monitoring and management, allowing biologists to count or tag fish as a means of abundance estimation. However, these monitoring efforts typically occur in isolation from the sociocultural context in which they evolved. Despite their historic importance and potential as contemporary fishing and management tools, traditional weirs are rarely used in First Nations fisheries or their management.

In 2013, we launched a collaborative initiative to revive traditional-style weir building at the Koeye River, on the Central Coast of British Columbia. The project is a collaboration between the Heiltsuk Nation, NGOs, and academics, providing a means of enumerating returning sockeye salmon (*Oncorhynchus nerka*). It also has a strong community engagement and educational focus. The goals of the project were to: (1) revitalize weir building within the Heiltsuk community of Bella Bella, (2) build long-term capacity for the stewardship of salmon resources within Heiltsuk Nation through training, education, and community outreach, and (3) develop a simple Bayesian mark-recapture method to produce estimates of population abundance that can inform local management. Here, we present our methods and findings from four years of operating a traditional-style weir, providing information on the techniques, materials, and best practices associated with weir construction and operation. We hope these experiences and insights can inform community-led salmon stewardship around the region, and inspire other culturally relevant monitoring initiatives which empower local communities in managing natural resources.

Methods

Weir construction – techniques and considerations

Weir design was based on images and archeological evidence from traditional salmon weirs (Figure 1) (e.g., Prince 2005; Stewart 2008). Built from a combination of locally harvested materials and modern building supplies, the basic design involves the construction of tripods which support a series of fence panels spanning the river, forming a barrier to the upstream movement of salmon. Fish are then forced to swim into an aluminum trap box, fitted with one-way trigger trap fingers from Neptune Marine Products. Traditional weirs were built from a variety of materials, including cedar, alder, and willow (Harris 2001). The Koeye River weir was built entirely from cedar because of its rot resistance, availability in the area, and the ease with which it splits (video S1). In total, the construction of the weir and associated tagging equipment cost approximately $8500 CAD. This simple design draws on the simplicity of ancient weir designs, using cost effective, locally sourced materials as well as affordable and widely available materials,

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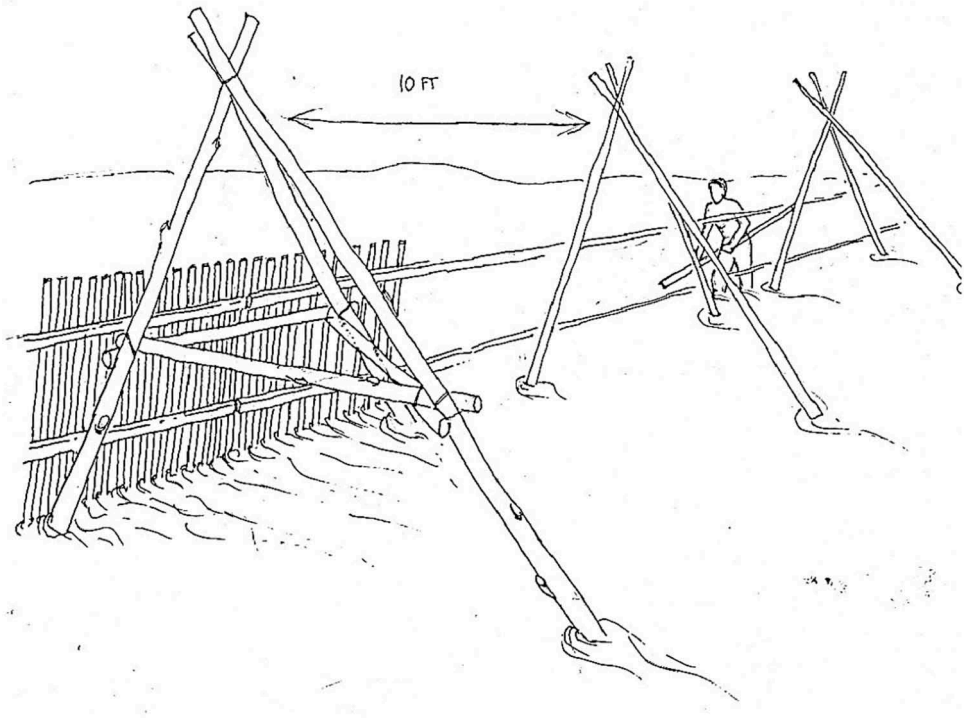

Figure 1. Original drawings of the design for the Koeye River weir. Sketches were based on historical images of fish weirs from around the Pacific Northwest. Courtesy of G. Callegari.

making it attractive for communities seeking to monitor or harvest wild salmon.

Weir operation

The weir is installed each year on 1 June and operates until late-July. Fish are anesthetized with MS-222 (0.1 g/L), and tagged with colored t-bar anchor tags from FLOY tag and MFG (Figure 2). Tags are inserted behind the dorsal fin on both sides, allowing resighting and estimates of tag loss. Fish are then passed upstream of the weir to continue migrating to Koeye Lake, where they hold until spawning begins in mid-September. Unique tag colors are used for each week, creating color groups that can be identified visually during counts. Spawning fish are counted during regular fall visits to the tributaries of Koeye Lake. Live sockeye are counted and all tagged and untagged fish are recorded for mark-resight estimates.

Mark-resight model

Sockeye abundance is estimated from peak fall counts of live fish in the tributaries of Koeye Lake, using a

Figure 2. (a) Heiltsuk weir technician Richard Wilson-Hall releases a tagged sockeye. (b) The Koeye River weir pictured during June of 2015. The weir is built entirely from locally sourced materials and readily available construction supplies. Courtesy of B. DeRoy.

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Bayesian adaptation of the pooled-Petersen estimator (Chapman 1951) that incorporates tag loss and the effect of daily variation in river temperature on pre-spawn mortality of tagged fish. Daily mean and maximum temperature values were monitored at a station in the lower Koeye River using Hobo Pendant temperature loggers from Onset Computer. Annual temperature summary data (Table 1) reflect the weighted annual mean of daily peak temperatures during the sockeye migration, weighted by the number of fish tagged on a given day. We assume (1) that all live fish in the tributaries of Koeye Lake have an equal probability of being counted, (2) a closed population, and (3) that all fish have the same probability of losing a tag and the loss of each tag is independent. These assumptions are likely robust in our study system where fish migrate quickly through the lower river, then hold and mix in the lake for several months prior to spawning.

R_i is the number of fish tagged at the weir on day i. The number of fish tagged on day i surviving to the spawning ground ($n^t{}_i$) is modeled using:

$$n_i^t|R_i,\theta_i \sim \text{Binomial}\left(R_i,\phi_i\right),$$

where ϕ_i is the individual probability for tagged fish to survive to the spawning grounds. Temperatures in the lower Koeye River regularly exceed 20°C during June and July, and the link between warm temperatures and pre-spawn mortality for sockeye salmon is well established (e.g., Crozier, Scheuerell, and Zabel 2011). Lacking information on the survival of individual fish tagged within the Koeye River, we modeled the effect of temperature on pre-spawn mortality based on other sockeye salmon populations (Crozier, Scheuerell, and Zabel 2011), using the logistic function:

$$\phi_i|a,b,T_{50} = \frac{a}{1+e^{-b(Tmax_i-T_{50})}},$$

where $Tmax_i$ is the maximum temperature on day i; a, b, and T_{50} are parameters that are given normally distributed prior distributions with mean and variance values obtained from Crozier, Scheuerell, and Zabel (2011) (Figure 3). For a, the maximum rate of en route mortality, the mean was set to 0.9 with a standard deviation of 0.015. For b, the rate at which survival declines with temperature, the mean was set to −1.78 with a standard deviation of 0.38. Finally, for T_{50}, the temperature at which 50% of fish die before spawning was set at 19.25°C with a standard deviation of 0.09.

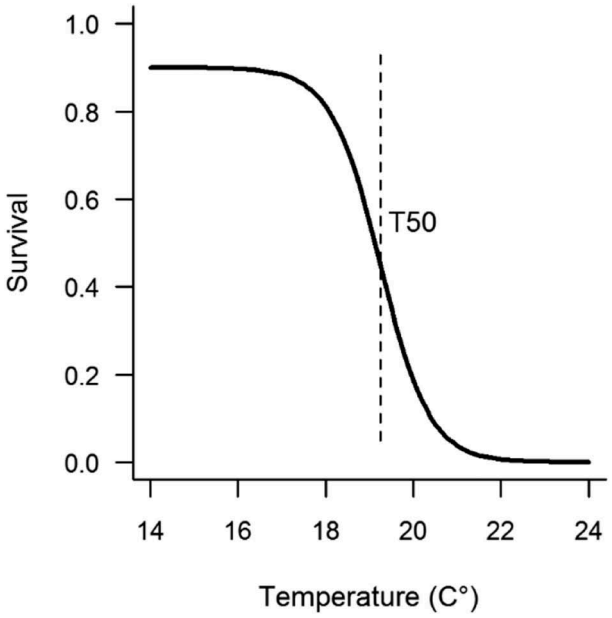

Figure 3. The logistic survival function relating maximum daily river temperature to survival of migrating adult sockeye salmon. The dashed line indicates the T50 value – temperature at which 50% of migrating adults die prior to spawning – and was set to 19.25°C° based on Crozier, Scheuerell, and Zabel (2011).

To account for potential tag loss, we tagged each fish twice – once on each side of the dorsal muscle – and modeled the total number of tagged fish surviving to the spawning grounds as $N^t = \sum_{i=1}^{K} n_i^t$, with an unknown number of them making it with two tags, one tag, or no tags. We denote those quantities by $N^{t,2}$, $N^{t,1}$, and $N^{t,0}$, respectively, and modeled their distribution as

$$\left(N^{t,0},N^{t,1},N^{t,2}\right) \sim \text{Multinomial}\left(N^t;\left(\theta^2,\theta,1-\theta^2-\theta\right)'\right),$$

where θ is the probability of losing one tag, and the loss of each tag is independent. We used a vague uniform(0,1) prior distribution on θ.

The count of tagged fish with two tags, $Y^{t,2}$, and the count of tagged fish with one tag, $Y^{t,1}$, are modeled using binomial distributions:

$$Y^{t,2}|N^{t,2},p \sim \text{Binomial}\left(N^{t,2},p\right);$$
$$Y^{t,1}|N^{t,1},p \sim \text{Binomial}\left(N^{t,1},p\right),$$

where p represents the individual probability of a fish being detected during the fall counts. A vague uniform (0,1) prior distribution is used on the parameter p.

Table 1. Number of fish tagged at the weir for all years of the study, average annual temperature weighted by the daily number of fish tagged, with estimates of the number surviving to spawn, the total spawning ground counts and number of fish resighted, as well as the resulting spawner estimate. For estimated survival and abundance, we report mean estimates and 95% credible intervals from the Bayesian mark-recapture model.

Year	Tagged	Temp. (°C)	Survival est.	Count/recap	Spawner est.
2013	233	17.5	158 (CI 146–170)	2149/71	4685 (CI 3877–5690)
2014	242	16.3	195 (CI 183–208)	NA	NA
2015	562	20.3	158 (CI 131–186)	2769/91	4.671 (CI 3756–5793)
2016	193	15.4	177 (CI 166–187)	3118/36	15,275 (CI 11,460–20,528)

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The count of untagged fish, Y^u, is modeled using a binomial distribution based on the unknown total number of untagged fish surviving to the spawning grounds, N^u, as well as the unknown number of tagged fish that lost both of their tags, $N^{t,0}$:

$$Y^u|E, N^u, N^{t,0}, p \sim \text{Binomial}\left(N^u + N^{t,0}, p\right).$$

We express the quantity N^u as $N^u = E - N^t$, where E is the unknown total spawner escapement, for which we use a vague normally distributed prior distribution, truncated above 0 and rounded to the nearest integer, with a mean of 5000 and a standard deviation of 50,000. For all mark-recapture parameters, the use of vague priors limits the degree to which prior information influences model estimates.

Our Bayesian analysis was implemented using R and JAGS software. Three chains were run for 100,000 iterations with a burn-in period of 5000 iterations. Convergence of the algorithm was assessed using traceplots. Parameter estimates were taken as the mean of the marginal posterior distributions and 95% quantile-based credible intervals.

Progress and perspectives

Over the four years of the study, we tagged between 193 and 562 sockeye per year, enabling annual mark-resight estimates of population abundances (Table 1). However, high flows and tides occasionally provided windows for unimpeded passage. In 2015, we adopted the practice of opening the weir on a regular basis, minimizing unnatural delays and reducing the risk of pre-spawn mortality from warm water temperatures and handling. Prior to opening the weir, we conducted seine sets in the pool downstream, leading to increased capture rates and tagging success. In 2016, we again opened the weir regularly; the weir was damaged on 3 July by a bank-full flow event, bringing the season to an early end. However, prior to the end of the 2016 weir season, we tagged 193 adult sockeye.

Fall counts in the two tributaries of Koeye Lake during late-September and early-October yielded a mean of 2678 sockeye, with an average proportion of tagged fish resighted of 22% across the four years of study. Estimates of spawner escapement varied across years, with a low of 4671 (CI 3756–5793) in 2015, and a high of 15,275 (CI 11,460–20,528) in 2016. Estimated temperature-mediated pre-spawn mortality varied considerably across years owing to a high degree of variability in June and July water temperatures. In 2015, the warmest year during the study period, the predicted rate of pre-spawn mortality for tagged sockeye was 72% (CI 67–77%). Contrasting with this high mortality was 2016, when temperatures remained cool throughout the migration season and estimated mortality was only 8% (CI 3–14%) (Table 1). High water and anomalously high densities of spawning pink salmon in the fall of 2014 made it impossible to count and resight tagged sockeye in the tributaries of Koeye Lake. Consequently, run size for that year is unknown.

Working with the Heiltsuk Nation and QQs Projects Society, a community-driven NGO, the project has built capacity in the Heiltsuk community of Bella Bella, employing and training 10 technicians over the first four years of the project. The learning and professional development of these individuals over four years provides a foundation for the ongoing success of Heiltsuk-led resource stewardship efforts, and many who have moved on to other employment remain in natural resource management jobs. The weir has also supported educational outreach. We work closely with the Bella Bella community school, and have hosted 12 field trips bringing close to 200 students to the weir, to learn about Heiltsuk cultural practices related to harvesting and stewardship of salmon. Campers at QQs' Koeye summer camp also make regular visits to the weir.

Conclusions

The Koeye River weir has revitalized the practice of weir building in the Heiltsuk community of Bella Bella. The well-being of First Nations communities is inextricably linked to the land and resources which have sustained them for millennia. By building capacity for the stewardship of FSC sockeye fisheries, and creating an opportunity for education and outreach, the weir is contributing to ongoing cultural and social revival among the Heiltsuk. By fusing a traditional management system with contemporary quantitative approaches to population monitoring, the weir and associated fall counts have produced rigorous estimates of sockeye salmon abundance. The model accounts for annual variability in temperature-mediated survival and tag loss, and expands count data collected during the fall spawning period to an estimate of sockeye escapement. The resulting estimates of population size range from 4600 to 15,000 across the four-year period of study, with up to 70% pre-spawn mortality for tagged fish in the warmest year. Historical data on water temperature are lacking; however, the summer of 2015 was among the hottest and driest on record for the BC Coast (Anslow 2016), suggesting warm water temperatures and elevated risk of pre-spawn mortality may become more regular occurrences under future climate conditions. These data provide a foundation for understanding the status of salmon in the Koeye River system, and the potential for climate-driven changes in the survival and productivity of sockeye salmon. Overall, sockeye salmon in the Koeye River appear to be stable and remain capable of supporting

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sustainable FSC fisheries. Ongoing tagging and enumeration will provide greater insight into the effects of climate on survival, and facilitate estimates of population productivity and carrying capacity, allowing the Heiltsuk to set escapement targets that limit the risk of overfishing under current and future climate conditions.

Fishing remains a vital part of the economy and culture of British Columbia's coastal First Nations. However, centralized and data-intensive scientific approaches to fisheries management will be insufficient for the management of small-scale fisheries if programs fail to build local capacity through employment and training, and are not rooted in local knowledge and values (Berkes 2003). The fusion of traditional and local knowledge with scientifically rigorous monitoring and management provides a promising avenue toward sustainable fisheries. Efforts to promote and develop community-driven management and traditional approaches to resource stewardship have shown promise in increasing abundance of economically important species (Groesbeck et al. 2014; Frid, McGreer, and Stevenson 2016), and can bolster the sustainability of fisheries (Aswani and Hamilton 2004; Defeo et al. 2014). Hybrid management systems which integrate local knowledge with science may also be effective tools for helping communities avoid or escape social-ecological traps (Aswani et al. 2007). Salmon weirs have been used for at least 5000 years as an effective means of selective harvest and management (Moss and Erlandson 1998). Our findings highlight the utility and feasibility of using traditional-style salmon weirs for some monitoring applications, particularly in smaller rivers with relatively stable hydrographs. These approaches may be particularly valuable in instances where cultural and educational objectives of local communities overlap with the goal of enumerating adult salmon.

Academics and government scientists are increasingly forging meaningful partnerships with indigenous communities, and the reciprocal exchange of knowledge and ideas should be at the foundation of these collaborations (Adams et al. 2014). First Nations across Canada are asserting their rights as stewards of their traditional territories, and given the well-documented erosion of government monitoring and legal frameworks for habitat protection (Price et al. 2008; Hutchings and Post 2013), these communities will play a major role in shaping the future of lands and natural resources. While this shift in power back toward long-marginalized indigenous communities marks a major milestone in Canada's journey toward a more equitable relationship with First Nations, there is a critical need for scientific collaborations with local communities, supporting resource management, and informed decision-making. We hope that the Koeye River weir can provide a template for other communities seeking to understand and manage salmon populations, and serve as a powerful example of the creative approaches to resource monitoring and stewardship which can arise from collaborations between First Nations communities and academic scientists.

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