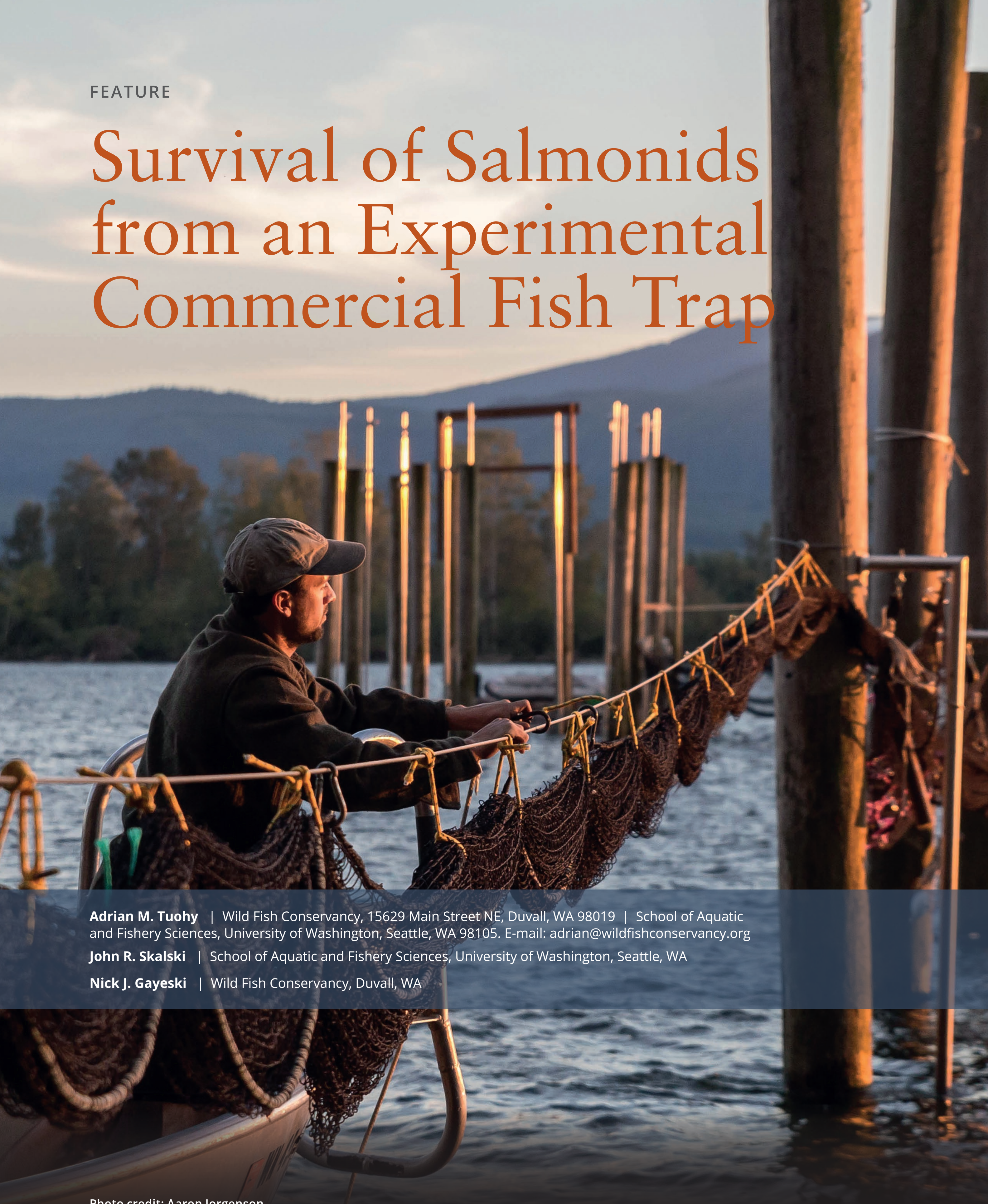
FEATURE

Survival of Salmonids from an Experimental Commercial Fish Trap



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Conventional harvest techniques used in mixed-stock commercial salmon fisheries frequently result in bycatch mortality, thereby impeding salmonid recovery and constraining fishing opportunities in the U.S. Pacific Northwest. To address the problem, a postrelease survival study was conducted in the Columbia River to evaluate the potential of an experimental salmon trap for stock-selective commercial harvest. A modified fish trap was constructed and operated in 2017, from August through September, with the goal of minimizing entanglement, air exposure, crowding, and handling of all captured fishes. Postrelease survival from the trap was estimated through a paired release–recapture study. Results demonstrate that the trap effectively targeted commercially viable quantities of hatchery-origin Chinook Salmon *Oncorhynchus tshawytscha* and Coho Salmon *O. kisutch* while reducing bycatch mortality rates relative to conventional commercial fishing gears. During the study, 7,129 salmonids were captured. The postrelease survival effect over a 400-km migration ranged from 0.944 ($\overline{SE} = 0.046$) for steelhead *O. mykiss* to 0.995 ($\overline{SE} = 0.078$) for Chinook Salmon, supporting the potential application of traps for stock-selective commercial harvest.

INTRODUCTION

Since the late 1800s, wild salmonids of the U.S. Pacific Northwest have declined dramatically from the cumulative effects of harvest, habitat loss, dams, and hatchery production (Lichatowich 1999). Europeans extirpated various wild salmonid populations shortly after their arrival to the region, and many remaining salmonid population groups are now listed for protection under the U.S. Endangered Species Act (ESA; Nehlsen et al. 1991; Anderson 1993; Quinn 2005). Despite many efforts to recover wild salmonids, production hatchery programs continue throughout the region in order to enhance short-term harvest opportunities in commercial, recreational, and tribal fisheries (HSRG 2014; Gayeski et al. 2018a).

The effect of harvest on wild salmonids is frequently compounded by hatchery production (National Research Council 1996; Lichatowich et al. 2017). By enhancing fisheries through hatchery production, resource managers increase mixed-stock fishing effort and bycatch mortality to threatened wild stocks that co-mingle with hatchery stocks during ocean rearing and the spawning migration. State, tribal, and federal (both U.S. and Canadian) agencies manage harvest to maximize catch of hatchery-origin fish—attempting to address the genetic and ecological problems associated with escapement of hatchery fish (Naish et al. 2007; Chilcote et al. 2011; Lichatowich 2013), while minimizing mortality to wild stocks mixed within regional fisheries (Canada DFO 2005; WFWC 2009; ODFW 2013). However, bycatch mortality and mixed-stock harvest can impede recovery efforts of ESA-listed stocks in lacking fishing gears that can selectively harvest targeted stocks (such as hatchery-origin fish) while leaving non-targeted fish (such as wild fish) unharmed (Wright 1993; Flagg et al. 1995; Gayeski et al. 2018b). Although mortality rates differ between species and fisheries across the West Coast, Chinook Salmon *Oncorhynchus tshawytscha* bycatch mortality from conventional gill nets ranges from 51% to 57% in the lower Columbia River (Vander Haegen et al. 2004). Considering the severe impact of gill nets on captured stocks, resource managers often approve the harvest and sale of wild salmon that may be ESA listed (ODFW 2017b) Furthermore, conventional harvest practices can reduce the diversity, size, fecundity, and age structure of wild populations, thus diminishing their survival, reproductive success, and capacity for adaptation to global climate change (Ricker 1981; Hamon et al. 2000; Lewis et al. 2015).

Given the depressed status of wild Pacific Northwest salmonids and the inadequacy of conventional gears for selective harvest of hatchery-origin salmon, regional management agencies have drastically constrained commercial salmon fishing opportunities in order to foster salmonid recovery (Martin 2008; NWFSC 2015; ODFW 2017a, 2017b). Despite these efforts and many others, ESA-listed wild salmonid stocks have not recovered, and fishing opportunities have become increasingly limited (Lichatowich et al. 2017; Price et al. 2017; Gayeski et al. 2018a). Failure to achieve Pacific salmonid recovery and the continued mixed-stock harvest of salmon in marine settings have further altered ecosystem dynamics. The populations of southern resident killer whales *Orcinus orca* and other apex predators have declined to historic lows due to reductions in the quantity and size of marine prey (e.g., Chinook Salmon) and other factors (Ford et al. 2010; Ayres et al. 2012; Lewis et al. 2015; Lacy et al. 2017).

With hatchery production continuing throughout the region (Lichatowich et al. 2017), implementing stock-selective fishing gears has been recognized as necessary for recovering ESA-listed salmonids and sustaining the participation of fishing communities (ODFW 2013; WFWC 2013; HSRG 2014). Removal of the adipose fin from hatchery-origin fish enables visual differentiation between wild and hatchery stocks (HSRG 2014). To capitalize on advancements in stock identification, meet ESA recovery objectives, and maximize utilization of fisheries allocations, resource management agencies in Washington and Oregon were directed to develop and implement alternative fishing gear to maximize catch of hatchery-origin fish with minimal mortality to native salmonids (WFWC 2009, 2013; ODFW 2013). Although alternative gear and postrelease mortality research conducted through paired mark–release–recapture has demonstrated some limited success in the region (Vander Haegen et al. 2004; Ashbrook 2008; WDFW 2014), few viable alternative fishing practices to date have been identified and implemented to address the bycatch problem associated with the harvest of hatchery-origin salmonids (HSRG 2014; Gayeski et al. 2018a). Furthermore, removal of the adipose fin for hatchery-origin stocks in the USA remains imperfect, compromising the effectiveness of selective harvest efforts (HSRG 2014).

Recognizing the limitations of previously evaluated alternative commercial gears in reducing stock-specific bycatch mortality rates, fisheries scientists and managers alike have recommended fish traps as another potential alternative to gill nets (Ashbrook 2008; Tuohy 2018). Historically, the fish trap was one of the most popular and efficient gears used throughout the Pacific Northwest in salmon fisheries (Cobb 1930; Lichatowich 1999). However, response to wild salmon declines and political pressure from gillnetting communities caused bans in the gear across the North American West Coast from the 1920s through the 1950s (Higgs 1982; Lichatowich 1999).

Fish traps are a form of fixed gear, meaning that the tool remains deployed in one place to passively capture fishes (Cobb 1921). If sufficiently regulated and operated with a conservation-minded approach, fish traps have the potential to lessen sublethal physiological effects in fisheries by reducing air exposure, overcrowding, entanglement, and handling of fish (Baker and Schindler 2009; Burnley et al. 2012; Raby et al. 2015). Furthermore, when used in fluvial settings, the fish trap allows for escapement of wild fish and does not deprive killer whales of the opportunity to secure the marine food resources required for their survival (Ford et al. 2010; Gayeski et al. 2018b).

The purpose of this study was to design, construct, and monitor the performance of a modified commercial fish trap in Washington State waters for the first time in over 80 years. Specifically, objectives were to estimate and compare immediate and postrelease bycatch mortality of wild fall Chinook Salmon and summer steelhead (anadromous Rainbow Trout *O. mykiss*) from an experimental fish trap relative to commercial gears that were previously evaluated in the lower Columbia River through paired mark–release–recapture (Vander Haegen et al. 2004; Ashbrook 2008; WDFW 2014). Given precise and unbiased estimates of catch composition and bycatch mortality for a fish trap, resource management agencies may evaluate the utility of using alternative commercial harvest gear for the recovery of wild salmonids and coastal fisheries in the U.S. Pacific Northwest.

METHODS

Trap Design and Study Location

Salmon traps or "pound nets" passively funnel returning adult salmonids along a lead positioned perpendicular to shore to a maze of walls and compartments (including the "heart" and "tunnel") for capture (Cobb 1921, 1930; Radke and Radke 2002). The final compartment, the "spiller," enables fish to swim freely within the trap until removal upon selective harvest or passive release (Cobb 1921; Tuohy 2018). In contrast to gillnetting, salmon that enter the spiller are captured without tangling of the teeth or opercula (Figure 1), thereby reducing physical injury and maximizing product quality (Baker and Schindler 2009; Tuohy 2018).

Based on historical trap designs, photographs, and anecdotes from the 1880s through the 1930s, untreated, 40.64-cm (16-in) diameter wood pilings were driven approximately 3–5 m apart in the Columbia River's Cathlamet Channel (Wahkiakum County, Washington) at river kilometer (rkm) 67, where salmon traps were once common prior Washington State's ban of fixed gear in 1934. This study site was a historically successful trapping location in the late-19th and early 20th centuries and was locally known for high abundances of salmon and steelhead. The experimental trap prototype consisted of a lead (~90 m), jigger (~10 m), heart (23-m length; 20-m maximum width), tunnel, and spiller (6 × 6 × 9 m), as well as a marine mammal deterrent gate at the entrance to the heart compartment (Figure 2). Black nylon mesh with a stretch of 7.94 cm was selected for application to the lead, jigger, and heart pilings (Christensen Net Works, Everson, Washington). The spiller and tunnel were constructed of 6.35-cm knotless-nylon mesh. Investigators selected these mesh sizes to minimize both the entanglement of fish and drag within the water column. All compartment nets were secured to the pilings from the bottom of the riverbed to about 1 m above the high-water mark, spanning approximately 8 m vertically. The marine mammal gate consisted of a series of vertical aluminum bars spaced at 25-cm increments to deter entry of mammals while enabling the passage of fish. The gate was hinged and could be opened or closed depending on the proximity of marine mammals to the study location.

The spiller/tunnel complex was engineered for deployment and retrieval to and from the river bottom with line and pulley. Steel weights at each corner of the compartment enabled gravity to draw the mesh flush to the river bottom during each soak period. A solar-powered electric winch was installed near the top of the pilings to pull the bottom mesh of the spiller upward through the water column to the shallows during each haul; this allowed captured fishes to be accessed swiftly from the depths of the river with minimal air exposure and stress. Adjacent to the spiller, a pontoon dock enabled sorting of the fish transferred from the spiller compartment within the confines of a perforated-aluminum framed live well (2.13 × 0.61 m). Within this compartment (holding capacity of ~40 adult salmonids), all fish remained free-swimming and submerged with continuously circulating river water. With the completion of a set, a small door to the live well was opened, allowing all captured fish to swim upstream with minimal handling.

Field Protocol

The study was conducted at the experimental trap site from August 26 through September 27, 2017. This late-summer to

Figure 1. Trap operators corralled fish in the shallows from the spiller to a live well with line, pulley, and a solar-powered winch. All captured fish could then be sorted for data collection and PIT tagging.

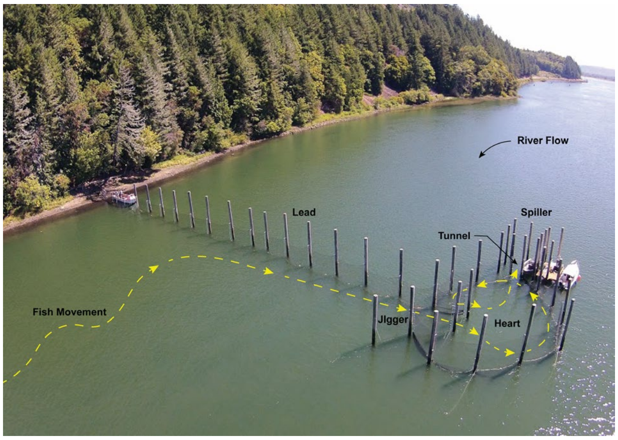

Figure 2. The experimental fish trap in the Columbia River (river kilometer 67) consisted of a lead, jigger, heart, tunnel, and spiller.

early fall period represented the peak of fall Chinook Salmon, Coho Salmon *O. kisutch*, and steelhead upriver migration in the lower Columbia River (Healey 1991). Hatchery-origin Chinook Salmon and Coho Salmon are commercially lucrative target stocks within the lower Columbia River fall fishery. Wild-origin summer steelhead, fall Chinook Salmon, and Coho Salmon populations are ESA listed and constitute common bycatch stocks that can constrain commercial fishing opportunities within the conventional fall fishery.

At the beginning of each fishing event, trap operators deployed the spiller to the river bottom and opened the tunnel door, initiating the soak period and enabling the capture of fishes. Investigators noted the beginning set time, tidal stage (m), tide height (m), water temperature (°C; Extech), and presence of marine mammals. The tunnel door remained open to fish passage until the capacity of the live well was visually determined to have been reached (minimizing potential physiological effects of overcrowding). During trap operation, the marine mammal deterrent gate was periodically closed to prevent entry of harbor seals *Phoca vitulina* and California sea lions *Zalophus californianus* to the heart and spiller compartments.

Once the soak period had ended (generally 3–60 min), the tunnel door was closed, preventing further fish entry or escape. Operators then lifted the spiller bottom using an electric winch to guide fish upward in the water column, concentrating captured fish in the shallows toward the spiller door (positioned adjacent to the live well of the sorting deck). Once the fish were guided into the live well, study investigators enumerated, measured (FL), and identified all specimens by species and origin (adipose fin clipped or unclipped, suggesting hatchery or wild origin, respectively). All adult Chinook Salmon and steelhead (except for those that escaped the handling and tagging process) were scanned for PIT tags with a Biomark 601 reader (Biomark, Boise, Idaho). If existing PIT tags were detected, codes were recorded directly into a computer database using P4 software (PTAGIS 2017); these fish were then passively released from the live-well chamber. In the absence of an existing PIT tag, adult Chinook Salmon (>57 cm) and steelhead were tagged in the peritoneal cavity with a 12.5-mm, 134.2-kHz, full-duplex PIT tag using an MK-25 Rapid Implant Gun (Biomark); each fish was scanned, and its tag number was recorded. In addition, 99.3% of PIT-tagged Chinook Salmon and steelhead also received a non-lethal 2-mm caudal fin clip for genetic analysis. Unique genetic sample numbers were recorded simultaneously with the PIT tag code of the tagged fish by utilizing P4 software. The PIT-tagged fish were placed into a recovery chamber of the live well with continuously recirculating river water (Farrell et al. 2001), after which they were passively released through the live-well door, and additional sets were performed. Due to the potential for upstream harvest and human consumption, fish were not anesthetized during the handling process.

Paired Release–Recapture Study

A paired mark–release–recapture methodology was used to estimate relative postrelease survival of fall Chinook Salmon and steelhead from the experimental trap to upstream detection points at main-stem dams (Cormack 1964). Although many Coho Salmon were encountered at the trap, mark–release–recapture was not performed due to the tendency of this species to spawn below upstream detection points. Mirroring prior alternative gear studies in the lower Columbia River, control and treatment groups of Chinook Salmon and steelhead were sourced at the study location, PIT-tagged, and released. The treatment group experienced commercial capture procedures that may impact survival after release. The control group did not undergo commercial capture procedures, and the fish were sourced one at a time with a rubberized dip net. As in all prior Columbia River alternative gear studies, hatchery- and wild-origin fish of each species were pooled to increase statistical power (assuming that rearing origin has no effect on adult in-river survival).

During each test-fishing day, control and treatment tagging sessions were generally assigned alternately. We employed these methods to reduce potential for violation of the following model assumptions: (1) the fate of each fish is independent; (2) control and treatment fish have equivalent handling and tagging survival; (3) control and treatment fish have equivalent stock composition, marine mammal predation, harvest pressures, environmental stressors, and tag loss; (4) all treatment fish have equal survival and recovery probabilities; (5) all control fish have equal survival and recovery probabilities; and (6) survival of handling/tagging effects is independent of in-river upstream survival. It must be noted, however, that there was some limitation to alternating control and treatment group tagging events due to water clarity, which affected the ability of field staff to randomly handle the catch. This increased the potential for unequal stock composition and recovery probability between control and treatment groups.

The treatment group consisted of individuals that were lifted en masse (mean = 19 adult salmonids) by the winch and spilled from the pound-net spiller to the live well. This process of capture mirrored how the gear would be operated in a commercial setting given the current status of fish trap engineering. After PIT-tagging and fin-clipping procedures were complete, fish were released from the live-well recovery chamber for upstream detection at PIT tag arrays (WDFW 2014).

A control group of Chinook Salmon and steelhead was passively captured at the project site, tagged, and released for detection upstream. Unlike the treatment fish (which experienced commercial capture procedures and made physical contact with the spiller mesh), the control fish were guided through the water on an individual basis with a rubberized dip net at the trap site to be handled in a live well for tagging, genetic sampling, and release.

Tag detection information from upstream arrays was accessed through the PIT Tag Information System (PTAGIS), which provides public access to the PIT tag data (PTAGIS 2017). Tag information was attained through upstream interrogations at dam and hatchery arrays. Main-stem dam array stations in the Columbia River basin are known to have detection rates over 99% (WDFW 2014).

Survival Analysis

A pair of Cormack (1964) single release–recapture models (a special case of the Cormack–Jolly–Seber model; Cormack 1964; Jolly 1965; Seber 1965) was used to estimate postrelease survival of treatment Chinook Salmon and summer steelhead relative to controls (τ) between the capture and release site (rkm 67) and upstream detection sites at Bonneville Dam (rkm 234), The Dalles Dam (rkm 309), and McNary Dam (rkm 470) on the Columbia River main stem

(Figure 3). The joint probability of survival and detection was also estimated for pooled detection sites above McNary Dam (Figure 3). The joint-tagging model helped to separate the effects of survival from detection and to adjust for the control effects of handling and tagging (Cormack 1964; Jolly 1965; Seber 1965). Analogous to prior Columbia River alternative gear survival studies that used the Ricker relative recovery method (Ricker 1958; Ashbrook 2008; WDFW 2014), immediate survival (τ_0) from capture to release from the gear, short-term survival (τ_1) from release to Bonneville Dam, long-term survival from Bonneville Dam to McNary Dam (τ_2 and τ_3), and cumulative survival ($\tau_0 \times \tau_1 \times \tau_2 \times \tau_3$) from initial capture at the trap site to McNary Dam were estimated (Figure 3). However, use of the Cormack (1964) release–recapture model for this study enabled estimation and correction for possible differences in treatment-specific detection probabilities (Cormack 1964; Jolly 1965; Seber 1965). Furthermore, it must be noted that the capture/release site used for this pound trap study differed from that used in previous postrelease survival studies. The tag-and-release locations for purse-seine, beach-seine, and tangle-net studies were between rkm 209 and 233 of the Columbia River (Ashbrook 2008; WDFW 2014). Our experimental trap was located at rkm 67. The consequence is that survival in this study is measured over a greater distance and duration and hence might be expected to be lower than that in past studies.

A Cormack (1964) single release–recapture model was used to describe the observed detection histories of the tagged fish at four upstream detection sites (i.e., Bonneville, The Dalles, and McNary dams and detection sites above McNary Dam). With four upstream detection sites, there were $2^4 = 16$ possible unique detection histories that could be observed for each of the control and treatment groups. The joint likelihood for the tagging study was expressed as a product of two multinomial distributions: the first describing the probability of seeing the control capture histories, and the second describing the probability of the treatment histories:

$$L(S_i,\tau_i,\vec{p}_{ci},\vec{p}_{ti},\lambda|R_c,\vec{m}_{ci},R_t,\vec{m}_{ti})=\binom{R_c}{\vec{m}_{ci}}\prod_{i=1}^{16}P_{ci}^{m_{ci}}\cdot\binom{R_t}{\vec{p}_{ti}}\prod_{i=1}^{16}P_{ti}^{m_{ti}} \tag{1}$$

where, R_c = number of control group fish that were tagged and released, m_{ci} = number of control group fish with detection history i (i = 1, …, 16), P_{ci} = probability of capture history i for the control group, R_t = number of treatment group fish that were tagged and released, m_{ti} = number of treatment group fish with detection history i (i = 1, …, 16), and P_{ti} = probability of capture history i for the treatment group.

The probabilities for the various detection histories were in turn expressed as functions of reach survival, site-specific detection probabilities, and reach-specific treatment effects, where, S_i = survival probability in reach i for control group fish (i = 1, …, 3), p_{ci} = probability of detection at location i for control group fish (i = 1, …, 3), p_{ti} = probability of detection at location i for treatment group fish (i = 1, …, 3), τ_i = treatment effect on survival in reach i (i = 1, …, 4), and λ = joint probability of survival and detection in the last reach between McNary Dam and all upstream PIT tag sites for control group fish (e.g., $\lambda = S_4 \times p_4$).

For instance, the probability of a control fish being detected at all four upstream locations was modeled as

$$p_{c[1111]}=S_1p_{c1}S_2p_{c2}S_3p_{c3}\lambda,$$

while a treatment fish with the same detection history had the probability of occurrence

$$p_{t[1111]}=(S_1\tau_1)p_{t1}(S_2\tau_2)p_{t2}(S_3\tau_3)p_{t3}(\lambda\tau_4).$$

Other detection histories were modeled analogously. As specified, the τ_i estimate is the survival of the treatment fish relative to the control fish (i.e., $\tau = S_{treat}/S_{control}$) on a reach-specific basis. Using this model formulation, the relative survival effects and their SEs were directly estimated by maximum likelihood estimation.

Unique detection histories at upstream dams were downloaded from PTAGIS. Previously PIT-tagged fish that were captured at the trap (tagged as juveniles or previously tagged at the trap site; N = 13) were excluded from the analysis due to the potential difference in handling survival relative to fish that had undergone the standard tagging procedure. Tag data were processed through the R platform and uploaded to Program USER (Skalski and Millspaugh 2006; http://www.cbr.washington.edu/analysis/apps/user) to estimate parameters of the joint likelihood model (Equation 1), including the treatment effects on postrelease survival, SEs, and the 95% profile likelihood confidence intervals (CIs). Program USER provides a convenient means of constructing multinomial and product multinomial likelihoods and numerically solving for maximum likelihood estimates and associated SEs. The most parsimonious model for parameter estimation was selected through a likelihood ratio test (LRT; Kendall and Stuart 1977). The LRT was used to test for homogeneous detection probabilities for control and treatment group fish (i.e., $p_{ci} = p_{ti}$, $\forall_i$) at $\alpha = 0.05$ (two-tailed).

Genetic Analysis

To ensure that there was equivalent stock composition between treatment and control groups (random assignment), the Conservation Genetics Lab (University of Montana) and the Eagle Fish Genetics Lab (Idaho Department of Fish and Game) analyzed 507 randomly selected Chinook Salmon genetic samples (241 control; 266 treatment) with Columbia River basin-specific single-nucleotide polymorphism markers. Chinook Salmon were selected for genetic analysis due to this species' propensity to return to tributaries below main-stem arrays in the study region (in contrast with steelhead, which were primarily destined for hatcheries and spawning grounds above McNary Dam). Since approximately 20% of Columbia River basin fall Chinook Salmon were forecasted to return to spawning grounds and hatcheries of major tributaries below Bonneville Dam (including the Willamette, Cowlitz, Lewis, and Kalama rivers; ODFW 2017a), genetic tests were used to assign individuals to natal populations either below or above Bonneville Dam with a 90% probability threshold (Piry et al. 2004; Miller et al. 2018). Given that Chinook Salmon and steelhead were randomly sampled and assigned to groups in identical fashion, Chinook Salmon genetic analyses were assumed to be sufficient for determining overall random assignment to treatment and control groups for both Chinook Salmon and steelhead.

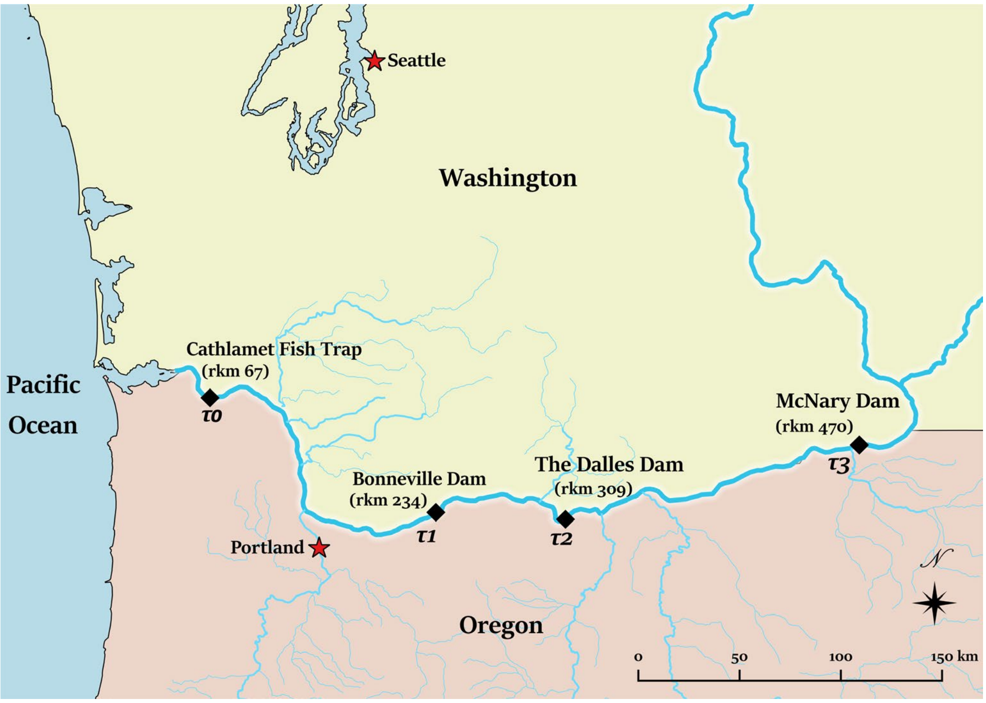

Figure 3. The effect on postrelease survival (τ_i) was estimated between the capture and release site at the experimental fish trap (river kilometer [rkm] 67) and the PIT tag arrays at upstream detection points: Bonneville Dam (rkm 234), The Dalles Dam (rkm 309), and McNary Dam (rkm 470). The last detection field consisted of all adult PIT tag detectors above McNary Dam.

Generalized linear modeling (GLM) based on a log-link and Poisson error structure was used in R (R Development Core Team 2008) to test the null hypothesis of homogeneity of Chinook Salmon population assignment to control and treatment groups at the $\alpha \le 0.05$ significance level. This GLM test of homogeneity was used to evaluate the assumptions of random arrangement of fish to control and treatment groups. However, genetic population assignment in the Columbia River basin remains coarse due to the homogenizing effects from hatchery genetic introgression, limiting finer-scale genetic assignment and evaluation of stock composition equivalence (Myers et al. 2006; Hess et al. 2014).

RESULTS

Total Catch

Study investigators fished the experimental trap for 290.5 h over 33 d between August 26 and September 27, 2017. Water temperatures were consistently greater than 18°C within the Columbia River main stem and episodically reached 22°C (Columbia Basin Research 2018). During the study period, 381 sets were performed, with a median soak length of 36 min (mean = 46 min; SD = 36). A median of 13 combined jack and adult salmonids were spilled to the live well per set (mean = 19 salmonids; SD = 20).

In total, 7,129 salmonids were captured. Total catch comprised 49.1% Coho Salmon (3,501 total; 52.4% were adipose fin-clipped; 16.4% were jacks [<55 cm]), 37.4% Chinook Salmon (2,670 total; 47.9% were adipose fin-clipped; 16.3% were jacks [<57 cm]), 12.9% summer steelhead (921 total; 80.9% were adipose fin-clipped), 0.4% resident/residualized (<30 cm) Rainbow Trout (29 total; 77.8% were adipose fin-clipped), and 0.1% unidentified salmonids *Oncorhynchus* spp. (8 total fish). In addition to salmonid catch, we captured and released three American Shad *Alosa sapidissima*, one Largemouth Bass *Micropterus salmoides*, one Common Carp *Cyprinus carpio*, and one Peamouth *Mylocheilus caurinus*. The marine mammal deterrent gate was deployed 81 times over the course of 381 sets, with marine mammal entry to the heart occurring on 11 occasions (primarily due to operator error).

Survival of Chinook Salmon

Throughout the duration of the study, a total of 2,066 Chinook Salmon were PIT-tagged (976 control; 1,090 treatment), with only one adult suffering immediate mortality ($\hat{\tau}_0 = 0.9995$). The LRT found no significant difference in PIT tag array detection probabilities for control and treatment groups ($\chi^2_3 \ge 0.364$, $P = 0.948$), resulting in a reduced model with common detection probability (i.e., $p_{ci} = p_{ti}$; $i = 1, \ldots, 3$). Postrelease survival for the treatment group compared to the control group was high from release to Bonneville Dam (~150 km upstream; median travel duration = 6 d) at a $\hat{\tau}_1$ of 0.970 ($\widehat{SE} = 0.036$; Table 1). The treatment group survived at a higher rate than the control group between Bonneville Dam and The Dalles Dam, with the estimate of relative survival increasing in this reach to a $\hat{\tau}_2$ value of 1.060 ($\widehat{SE} = 0.051$). Relative release survival from The Dalles Dam to McNary Dam declined slightly but remained high at a $\hat{\tau}_3$ of 0.968 ($\widehat{SE} = 0.049$). Cumulative relative survival for the treatment group from capture at the trap site to McNary Dam (~400 km upstream; median travel duration = 13 d) was estimated to be 0.995 ($\widehat{SE} = 0.078$). The GLM/log-linear analysis of the genetic sample results indicated homogeneous population assignment to control and treatment groups ($\chi^2_1 \ge 0.000$, $P = 1.000$), suggesting equivalence in stock composition (Table 2).

Table 1. Relative treatment effects (i.e., relative survival $\tau = S_{treat}/S_{control}$) on postrelease survival by river reach for adult fall Chinook Salmon and steelhead, cumulative survival from the fish trap to McNary Dam (≈400 km), and associated 95% profile likelihood confidence intervals (CIs) are displayed.

	Chinook Salmon		**Steelhead**	
River reach	τ	**95% CI**	τ	**95% CI**
Immediate survival (τ_0)	0.9995	0.998–1.000	1.000	0.995–1.000
Trap to Bonneville Dam (τ_1)	0.9700	0.901–1.044	0.977	0.911–1.048
Bonneville Dam to The Dalles Dam (τ_2)	1.0600	0.965–1.166	0.983	0.935–1.032
The Dalles Dam to McNary Dam (τ_3)	0.9680	0.877–1.070	0.983	0.939–1.028
Cumulative ($\tau_0 \times \tau_1 \times \tau_2 \times \tau_3$)	0.9950	0.924–1.071	0.944	0.880–1.012

Table 2. A contingency table constructed based upon results of the generalized linear modeling/log-linear analysis for control and treatment group Chinook Salmon that were genetically assigned to a Columbia River basin population group (below or above Bonneville Dam). The observed frequency in each cell is shown, along with the frequency that would be expected (in parentheses) if there is no association between control and treatment group and the population group assignment.

Group	**Control**	**Treatment**	**Frequency**
Populations below Bonneville Dam	47 (46.91)	52 (52.09)	99
Populations above Bonneville Dam	188 (188.10)	209 (208.91)	397
Frequency	235	261	496

Table 3. Relative survival estimates from the experimental trap presented in comparison with lower Columbia River cumulative survival estimates and associated 95% confidence intervals (if available; in parentheses) from prior studies.

Gear	**Chinook Salmon survival**	**Steelhead survival**
Fish trap	0.995 (0.924–1.071)	0.944 (0.880–1.012)
Gill net (20.320–22.225 cm [8.00–8.75 in])	0.520[a]	0.552[b]
Tangle net (9.525 cm [3.75 in])	0.764[c]	0.764[d]
Beach seine	0.750 (0.710–0.790)[e]	0.920 (0.820–1.000)[e]
Purse seine	0.780 (0.720–0.850)[e]	0.980 (0.930–1.000)[e]

[a] IFSP 2014.

[b] TAC 2008.

[c] TAC 2018.

[d] WDFW and ODFW 2018.

[e] WDFW 2014.

Survival of Steelhead

Overall, 782 steelhead were PIT-tagged over the course of the study (379 control; 403 treatment), with zero adult immediate mortalities ($\hat{\tau}_0 = 1.000$). For summer steelhead, the LRT found no significant difference in PIT tag array detection probabilities for control and treatment groups ($\chi^2_3 \geq 6.874$, $P = 0.076$), resulting in selection of the reduced model with common detection probability. Postrelease relative survival for the treatment group compared to the control group was high from release to Bonneville Dam (~150 km upstream; median travel duration = 6 d) at a $\hat{\tau}_1$ value of 0.977 ($\widehat{SE} = 0.035$; Table 1). Release survival remained high in subsequent reaches from Bonneville Dam to The Dalles Dam ($\hat{\tau}_2 = 0.983$; $\widehat{SE} = 0.024$) and from The Dalles Dam to McNary Dam ($\hat{\tau}_3 = 0.983$, $\widehat{SE} = 0.022$; Table 1). Cumulative relative survival of the treatment group for adult steelhead from capture at the trap site to McNary Dam (~400 km upstream; median travel duration = 18 d) was 0.944 ($\widehat{SE} = 0.046$).

DISCUSSION

This study represents the first successful attempt to design, construct, and operate a commercial pound-net trap for the capture of salmon in Washington State waters in over 80 years. Furthermore, it is the first-ever evaluation of salmonid postrelease survival from a commercial-scale salmon trap. Results demonstrate the feasibility of the gear for stock-selective harvest, offering a possible solution to hatchery and bycatch problems within salmon fisheries of the U.S. Pacific Northwest. Based on the capture of 7,129 salmonids with the prototype design, it is evident that the traps can effectively capture fish for commercial harvest purposes. Furthermore, when operated with a conservation-minded approach, operators of the gear can successfully release the great majority of non-target salmonids unharmed (Table 3). Depending on the conservation issues present within a fishery, the fish trap is yet another tool with which to address bycatch, hatchery management, and recovery of ESA-listed stocks while enabling continuation of commercial fishing.

Bycatch Survival

Cumulative relative survival of Chinook Salmon released from the experimental trap represents a statistically significant ($P < 0.05$) and dramatic improvement over survival estimates produced from previous studies of alternative and conventional gears (Table 1). Analyzing the treatment effect on cumulative survival over a 400-km upriver migration and a median duration of 13 d for Chinook Salmon, the experimental trap outperformed all other gears used on the lower Columbia River, with cumulative relative survival estimated at 0.995 (95% CI = 0.924–1.071). This result was achieved with tagging operations occurring approximately 150 km farther downstream than prior bycatch mortality studies. Furthermore, capture procedures for the control group were likely less stressful than procedures used in previous Columbia River studies, during which fish were trapped at the Bonneville Dam adult fish passage facility, dipnetted, handled, PIT-tagged, and trucked downstream to the upstream end of the test fishing location at rkm 225 (Ashbrook 2008; WDFW 2014). Despite promising results from this study, further research should be conducted with the fish trap and other alternative gears to better understand the potential latent mortality effects of commercial fishing on salmonids destined for long-range upriver migration to spawning grounds (Baker and Schindler 2009; Bass et al. 2018). These investigations will require larger sample sizes to precisely estimate survival to spawning grounds or river reaches above McNary Dam in the Columbia River basin (Tuohy 2018).

For summer steelhead, cumulative relative survival from the experimental trap over a 400-km upriver migration and median travel duration of 18 d was 0.944 (95% CI = 0.880–1.012). This point estimate is a significant improvement over that of the gill net (Table 1) but is not significantly different than point estimates for the seine from prior Columbia River survival studies. These results suggest the need for further research to better determine which gear yields greater steelhead postrelease survival. It must be noted, however, that this analysis occurred over a far greater migration distance and longer postrelease duration than previous alternative gear analyses.

Catch Effectiveness

For commercial implementation of any alternative gear type, a fishing tool must not only demonstrate potential to achieve conservation objectives but also meet the economic needs of fishers and industry. Given the historical effectiveness and popularity of commercial fish traps throughout the U.S. Pacific Northwest (Cobb 1930; Lichatowich 1999), there is little reason to believe that modern trap designs (when well placed) would be less effective than conventional gears used within Pacific Northwest salmon fisheries. Although the design of this alternative gear study provided no means to precisely and accurately compare capture efficiency of trap operations to that of the conventional gill-net fishery, the performance of the experimental trap prototype suggests that the gear can once again be engineered to effectively capture salmon. Furthermore, coarse comparison with limited available evidence suggests that the trap captured at least a comparable quantity of combined hatchery-origin Chinook Salmon and Coho Salmon per hour relative to the average Columbia River gill-net vessel's combined harvest of both hatchery- and wild-origin fish of those species during overlapping periods of operation (ODFW 2017b; Tuohy 2018). Nevertheless, there is a need for further research under real-world commercial fishing conditions to evaluate and compare CPUE and assess the economic feasibility of the technology (e.g., total cost, revenue, and profit). The upfront costs of a trap are presently high and must prove surmountable and recoupable to fishers or cooperatives in order to produce anticipated long-term economic benefits (Tuohy 2018).

Potential Benefits

Retooling of commercial gillnetting fleets to lower-impact alternative gear types such as fish traps could provide substantial benefit to the Pacific Northwest salmon fishing industry (Gayeski et al. 2018b). Presently, commercial gillnetting opportunity is constrained from the onset of the fishing season; this is due in part to high bycatch mortality rates and ESA conservation and management concerns (Vander Haegen et al. 2004; Martin 2008). Considering gill-net impacts to ESA-listed stocks, harvest and allocation negotiations frequently result in limited fishing for the commercial fleet. For example, in fall 2017, the lower Columbia River commercial gillnetting fleet was authorized to fish on only seven occasions as a precautionary measure to protect low returns of ESA-listed steelhead (ODFW 2017b). In utilizing stock-selective harvest tools with low bycatch impacts to wild fish, commercial fishers would likely see greater allocations of the resource, lengthening the season and increasing profitability. Furthermore, commercial fishing fleets would be less prone to in-season closure from exceeding ESA take limits.

While enabling fishers to fish longer and more consistently, use of viable stock-selective harvest tools with substantially reduced bycatch impacts could enable more Pacific salmon fisheries to become certified sustainable in the marketplace, returning a greater price per unit weight (Gayeski et al. 2018b). Sustainable market certifiers brand seafood products in the marketplace that meet specific sustainability criteria. This branding can result in product differentiation to consumers and increased prices received by fishers and processors (Cooper 2004; Kaiser and Edwards-Jones 2006; Gayeski et al. 2018b). Concurrently, value-added practices (including bleeding and icing the fish on site, and direct marketing of a higher-quality live-captured product to restaurants and other buyers) could help retooled fisheries increase profitability (Johnson 2018). Transitioning to alternative gears and utilizing value-added practices in certified-sustainable fisheries could improve economic prospects within the industry, increasing fishing opportunity and the prices received for harvested products (Gayeski et al. 2018b).

For threatened and endangered wild salmonids in the Pacific Northwest, reduction of hatchery and bycatch impacts could prove essential to their survival and recovery (Lichatowich et al. 2017). The percentage of hatchery-origin spawners continues to exceed hatchery management targets, with many spawning populations in the region experiencing percentages of hatchery-origin spawners greater than 50% (reducing the fitness and survival of subsequent generations; Chilcote et al. 2011; HSRG 2014; WDFW 2018). Release mortality from gill nets remains significant, prompting management to allow harvest of both hatchery- and wild-origin salmon stocks indiscriminately in many Pacific Northwest fisheries (Buchanan et al. 2002; IFSP 2014; Teffer et al. 2017). Considering these impacts and the accelerating effects of global climate change, the need for selective harvest is urgent to improve targeting of hatchery-origin fish and escapement of wild salmonids (Lichatowich et al. 2017; Gayeski et al. 2018a).

Although transition from the ongoing fisheries management paradigm of production hatcheries and conventional harvest will prove challenging, change may be necessary to prevent further wild salmonid declines, degradation of genetic and life history diversity, and curtailment of fishing opportunities (Schindler et al. 2010; Lichatowich et al. 2017; Gayeski et al. 2018a). Partial solutions are at hand (e.g., stock-selective commercial harvest tools) to help remedy harvest and hatchery problems in the region. Despite the short-term discomfort that may be caused by changes in harvest strategy, long-term benefits from a well-orchestrated policy and management shift toward the use of stock-selective gears such as fish traps could improve the economic outcome for fishers and fisheries of the Pacific Northwest (Gayeski et al. 2018a). Use of traps could also reduce the challenges associated with commercial fisheries observation and enforcement and provide a means for low-impact ecological monitoring. Although further research is needed in other locations, seasons, and years, it is possible that the return to a historical fishery in the Pacific Northwest could prove to be a win–win situation for fishers, ESA-listed salmonid stocks, management, and the environment.

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DATA SHARING

All data for this study (including the results of genetic analyses) may be downloaded free of charge through the Wild Fish Conservancy webpage (www.wildfishconservancy.org) by clicking on the "Projects" and "Columbia River Pound Net Project" tabs. All PIT tag information can be accessed through the PTAGIS webpage (www.ptagis.com) utilizing the code "CPN" and name "Cathlamet Pound Net."

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