North American Journal of Fisheries Management

ISSN: 0275-5947 print / 1548-8675 online
DOI: 10.1002/nafm.10496

ARTICLE

Modified Commercial Fish Trap to Help Eliminate Salmonid Bycatch Mortality

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Abstract

The utility of commercial salmonid *Oncorhynchus* spp. traps in the U.S. Pacific Northwest was recently revisited for the first time in decades to enable selective harvesting of hatchery-origin salmonids while reducing mortality of Endangered Species Act (ESA)-listed salmonids. Modifications to historical gear designs resulted in dramatic improvements in salmonid bycatch survival rates relative to conventional commercial gears in the lower Columbia River. Expanding upon this work, an experimental commercial fish trap was further modified to largely eliminate net contact, air exposure, handling, and crowding of fish. Studies were conducted from May to November 2019 in the lower Columbia River to estimate survival of bycatch and evaluate potential benefits from the modified passive capture design. Analyzed through two separate survival estimation techniques, the modified trap demonstrated no detectable effect on salmon release survival and a significant improvement over the previous prototype design. Estimated through a paired release–recapture methodology, the relative survival effect of catch and release compared to controls over a 400-km migration was 1.017 (SE = 0.032) for adult Sockeye Salmon *O. nerka*. For adult Coho Salmon *O. kisutch* that were held captive for a 48-h postrelease period, estimated survival (S) was 1.000 (lower 95% confidence limit: $S \geq 0.978$). These results suggest that trap modifications can be made to significantly reduce bycatch mortality of ESA-listed salmonids and provide increased opportunity for harvest of hatchery-origin salmonids.

Many wild salmonid *Oncorhynchus* spp. evolutionarily significant units in the Columbia River basin of the U.S. Pacific Northwest are currently listed as threatened or endangered under the Endangered Species Act (ESA) and remain in decline as a result of harvest impacts, habitat loss, hatcheries, and climate change (Nehlsen et al. 1991; Lichatowich 1999; NWFSC 2015; Crozier 2016). This includes 13 evolutionarily significant units of wild-origin steelhead *O. mykiss* (anadromous Rainbow Trout), Chinook Salmon *O. tshawytscha*, Coho Salmon *O. kisutch*, Chum Salmon *O. keta*, and Sockeye Salmon *O. nerka* (NWFSC 2015). Hatchery production of salmonids is used

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Received February 21, 2020; accepted July 13, 2020

for mitigation purposes in the region, theoretically increasing short-term commercial, recreational, and tribal harvest opportunities (Utter and Epifanio 2002; Naish et al. 2007). Nevertheless, the practice often threatens ESA-listed wild salmonid populations both genetically and ecologically (Chilcote et al. 2011; Naman and Sharpe 2012; Christie et al. 2014). Furthermore, hatchery production encourages increased fishing effort with gears that cannot effectively release wild salmonid bycatch unharmed (NRC 1996; WDFW 1997; Hilborn and Eggers 2000; Naish et al. 2007). In the lower Columbia River fishery, gill nets cause approximately 43–49% mortality of ESA-listed salmonids that are captured and released (Vander Haegen et al. 2004; TAC 2008). This conventional fisheries management paradigm of hatchery production, coupled with bycatch from fisheries, has impacted the recovery of wild salmonid populations (WDFW 1997; Lichatowich et al. 2017; Gayeski et al. 2018b). Consequently, many commercial, recreational, and tribal fisheries of the Columbia River (and elsewhere in the U.S. Pacific Northwest) are increasingly constrained by ESA management concerns (Martin 2008; ODFW and WDFW 2019).

Recognizing the need for harvest and hatchery reforms to promote salmonid recovery in the Columbia River basin, fisheries managers directed the Washington Department of Fish and Wildlife and the Oregon Department of Fish and Wildlife to develop and implement alternative commercial gear to enable in-river selective harvest of hatchery-origin salmon and reduce bycatch impacts to ESA-listed wild salmonids (WFWC 2009, 2013; ODFW 2013). Alternatives to the conventional gill net—including beach seines, modified purse seines, and tangle nets—were tested between 2001 and 2016 in the lower Columbia River (Vander Haegen et al. 2004; Ashbrook 2008; WDFW 2014, 2016; Takata and Johnson 2018). Limitations to the effectiveness of these gears subsequently inspired calls for evaluation of fish traps to further improve bycatch survival relative to in-river gill nets through reduction of entanglement, air exposure, handling, and crowding of captured fish (Tuohy et al. 2019).

The fish trap was a historically effective gear, popular in both indigenous and commercial salmon fisheries of the U.S. Pacific Northwest (Cobb 1930; Lichatowich 1999). The fishing method was banned in Washington State in 1934 and Oregon in 1948 due to the perceived contribution of the gear to salmon decline in these mostly unregulated fisheries (Washington State Session Laws 1935; Johnson et al. 1948; Higgs 1982). Contrary to the specified intent of the ban, resource managers failed to reduce total fishing effort or to meet biologically acceptable escapement goals after 1934 (Johnson et al. 1948; Boxberger 1989; Lichatowich 2013). Shortly after the elimination of fish traps and other fixed gears, Columbia River and Puget Sound salmon fisheries collapsed (Lichatowich 1999).

In 2016, the Wild Fish Conservancy (a nonprofit organization) and a local commercial fisher constructed the first operational pile trap in over 80 years in the Columbia River's Cathlamet Channel (Wahkiakum County, Washington; river kilometer [rkm] 67 [rkm 0 = mouth of the Columbia River]; Tuohy 2018; Tuohy et al. 2019). The experimental trap was modeled after designs historically used in the lower Columbia River but was modified to minimize physical and physiological damage to salmonid bycatch. Postrelease survival from the trap was estimated through a paired release–recapture study in 2017. Results demonstrated that the trap effectively captured hatchery-origin Chinook Salmon and Coho Salmon while improving salmonid bycatch survival rates relative to conventional gill nets. Relative survival of trapped fish compared to controls over a 400-km migration was estimated at 0.944 ($\widehat{SE}$ = 0.046) for steelhead and 0.995 ($\widehat{SE}$ = 0.078) for Chinook Salmon (Tuohy et al. 2019).

Although the prototype trap design dramatically improved upon bycatch survival rates of gill nets and other previously evaluated gears (Tuohy et al. 2019), some salmonid populations remain so heavily depleted within the U.S. Pacific Northwest that commercial gears encountering these fish must achieve nearly 100% survival of salmonid bycatch for fishers to operate effectively within ESA impact constraints. The purpose of this study was to fill existing data gaps for Sockeye Salmon and Coho Salmon and further modify the 2017 prototype fish trap design to nearly eliminate salmonid bycatch mortality. Specifically, our objectives were to estimate and compare immediate and postrelease bycatch mortality rates of wild Sockeye Salmon and Coho Salmon from the modified fish trap design relative to results from the prototype trap and other previously tested commercial gears through paired release–recapture and a net-pen holding methodology (Vander Haegen et al. 2004; WDFW 2014; Takata and Johnson 2018; Tuohy et al. 2019). This information may be used by resource management agencies and fishers coastwide to assess the utility of alternative commercial gear to increase sustainable fishing opportunities, enable selective harvest in terminal river locations, and minimize bycatch mortality for wild salmonid recovery (Knudsen 2000; Lawson and Comstock 2000).

METHODS

Study area.— The 2019 fish trap was located at rkm 67 on the Columbia River in the Cathlamet Channel (Wahkiakum County, Washington). The trap occupied the same location as used in the prototype study of Tuohy et al. (2019); salmon traps were once commonplace in this area before the Washington State ban on fixed gear in 1934 (Washington State Session Laws 1935). The Cathlamet Channel is 1.1 km wide at this point in the river, with a maximum depth of 6.1 m at high tide and a minimum depth of 3.3 m at low tide. Daily tidal flux during the study ranged from 1.5 to 2.8 m.

Trap design and modifications.— By design, fish traps remain fixed in position by piling or anchor and passively funnel returning adult salmonids from the "lead" (a fine-meshed wall positioned perpendicular to shore) through a maze of mesh compartments from which fish rarely escape (Cobb 1930). Captured salmonids instinctively move against the current into progressively smaller compartments of the fish trap ("heart," "spiller," and "live well," respectively; Cobb 1930; Tuohy et al. 2019). The final compartment has dimensions appropriate for operators to sort the catch for harvest or passive release with little to no air exposure and handling. Salmonids remain free-swimming within the fish trap, and selected mesh dimensions minimize or prevent entanglement altogether (Tuohy et al. 2019).

Identical to the prototype described by Tuohy et al. (2019), the Cathlamet Channel fish trap consisted of a lead (~90 m), jigger (~10 m), heart (23-m length; 20-m maximum width), tunnel, and spiller (6 × 6 × 9 m; Figure 1). Black nylon mesh with a stretch of 7.94 cm was used for the lead and jigger (Christensen Net Works, Everson, Washington). The heart, spiller, and tunnel were constructed of 6.35-cm knotless-nylon mesh. Mesh sizes were

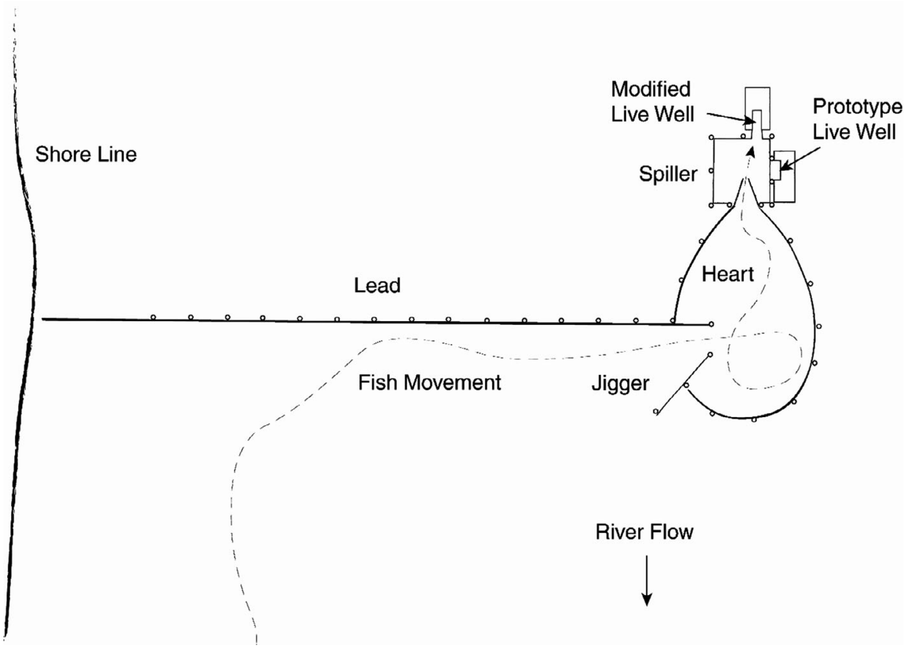

FIGURE 1. The fish trap constructed in Cathlamet Channel (lower Columbia River) consisted of a lead, jigger, heart, tunnel, and spiller.

FIGURE 2. The prototype spilling technique **(A)** used a line-and-pulley system and an electric winch to corral groups of captured fish to a live well for sorting. The modified passive design **(B)** employed an upstream tunnel from the spiller compartment to allow individual fish to migrate volitionally from the spiller to an attached upstream live well for sorting, with zero air exposure and net contact. [Color figure can be viewed at afsjournals.org.]

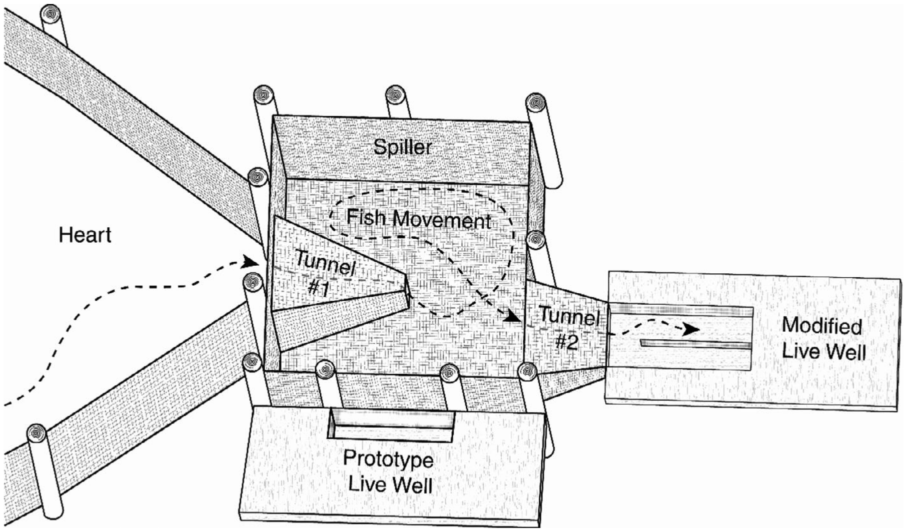

FIGURE 3. The modified trap design enabled free-swimming fish to be captured passively on an individual basis while eliminating air exposure and net contact from the commercial process.

carefully selected by study investigators to minimize entanglement of fish and minimize drag within the water column. All compartment nets were secured to untreated wood pilings (generally positioned 5 m apart) from the bottom of the riverbed to roughly 1 m above the high-water mark. As in the 2017 study, an aluminum marine mammal deterrent gate was installed at the entrance to the heart. This gate could be opened or closed to prevent entry of large mammals to the heart and spiller of the trap while maintaining some level of fish passage for harvest or data collection (Tuohy et al. 2019).

In efforts to improve the postrelease survival of captured fish from the gear, the spiller compartment and final capture processes were modified in 2019. In contrast with the 2017 prototype trap design (Tuohy et al. 2019: Figure 2A), a line-and-pulley electric winch system (henceforth, the “prototype treatment”) was no longer necessary for hauling the mesh bottom of the spiller/tunnel complex to the shallows for sorting of the catch (a procedure that may cause physiological stress or minor physical damage to captured fishes). A modified passive capture design (henceforth, the “modified treatment”) was implemented in 2019 by adding a new upstream tunnel to the existing spiller compartment (Figures 2B, 3). This upstream tunnel (6.35-cm knotless-nylon mesh) passively funneled migrating fishes from the spiller to the shallows of an attached upstream live-well trough. The live well was aluminum framed, with 3.81-cm knotless-nylon mesh walls to enable river water to constantly recirculate. It was equipped with two parallel rectangular chambers (2.74 × 0.61 × 0.76 m) and a mesh pivot capture door near the outlet of the upstream spiller tunnel. Operators could open or close the capture door to passively entrap migrating fishes in one chamber while enabling the vacant chamber to be occupied by fishes (Figures 2B, 3). Within the shallow live well, the free-swimming catch could be comfortably sorted by wading study investigators for harvest or data collection and passive release through an upstream mesh exit door. This 2019 modified trapping process largely eliminated fish air exposure, handling, overcrowding, and net contact associated with the 2017 prototype trapping process (with the intent of improving postrelease salmonid survival). Nevertheless, handling of fish within the live well remained necessary to restrain the catch for data collection purposes.

Research and test fishery operations.— Research and commercial fishing trials were conducted between May 5 and October 31, 2019, during peak migration periods for Sockeye Salmon and Coho Salmon in the lower Columbia River (Johnson et al. 1948; Burgner 1991; Sandercock 1991). Hatchery-origin Chinook Salmon and Coho Salmon are commercially targeted for harvest within Columbia River fisheries. Bycatch of ESA-listed steelhead, Chinook Salmon, Coho Salmon, Chum Salmon, and Sockeye Salmon evolutionarily significant units can considerably constrain commercial fisheries in the region (Martin 2008; NWFSC 2015).

To begin a fishing event, trap operators deployed the spiller from its suspended position above the water column to the river bottom. Tunnel doors were then opened, enabling the capture of free-swimming fish from the spiller compartment using one of three separate techniques: (1) the 2019 modified treatment, (2) the 2017 prototype treatment, or (3) a rubberized dip net (henceforth, the “control”). Investigators documented the beginning set time, tidal stage (ebb, flood, and slack), water temperature (°C;

Extech), presence of marine mammals, and the method of capture (modified treatment, prototype treatment, or control). Tunnel doors remained open to fish passage until a pause or cessation of fishing was desired. During trap operations, the marine mammal deterrent gate was occasionally closed due to the proximity of Steller sea lions *Eumetopias jubatus* and California sea lions *Zalophus californianus* to the project site.

Trap operators visually observed the spiller and upstream live well to determine fish entrance and occupancy through the modified treatment process. Once a live-well chamber was occupied by one or more fish, study investigators trapped the catch through closure of the capture door. Wading within the live well, biologists or fishers could then restrain fish by hand to enumerate, measure (FL), and identify all specimens by species and origin (adipose fin clipped [suggesting hatchery origin] or unclipped [suggesting natural origin]). All salmonids (except for those that escaped the live well) were scanned for PIT tags with a Biomark HPR Lite reader (Biomark, Boise, Idaho). If existing PIT tags were detected, codes were recorded using P4 software (PSMFC 2017); these salmonids were then allowed to passively migrate through the live-well exit door for detection upriver. To assess potential comparative benefits of the modified treatment process, adult salmonids were also captured individually through the control sourcing technique and en masse via the prototype treatment for data collection within a live well. Any fish that showed no signs of life at capture or release was analyzed for the cause of death and was noted as an immediate mortality.

Sockeye Salmon mark–release–recapture experimental design.— Similar to the 2017 fish trap study of Tuohy et al. (2019) and other alternative gear studies conducted on the lower Columbia River (Vander Haegen et al. 2004; WDFW 2014), a paired mark–release–recapture methodology was used to estimate relative postrelease survival of Sockeye Salmon exposed to commercial fish trapping processes (Burnham et al. 1987). Between May and August, Sockeye Salmon lacking an existing PIT tag (99.9% of those encountered) were randomly captured through treatment and control sourcing methods, assigned to corresponding treatment or control groups based upon the means of capture, restrained by hand within a live well, and 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). These fish were scanned to record PIT tag information, after which they were passively released through the live-well exit door for upriver detection. This paired mark–release–recapture approach was used to adjust for the physical and physiological effects of handling and PIT tagging, thereby isolating commercial treatment effects on adult salmon release survival in analysis.

During May–July operations, both treatment and control Sockeye Salmon were randomly captured and PIT-tagged so that each group was represented throughout the study period in nearly equal cumulative proportions. This effort to achieve proportional tagging over the course of the study helped to assure similar (1) handling and tagging effects, (2) stock compositions, (3) marine mammal and harvest pressures, and (4) handling, tag loss, and environmental stressors between groups.

The modified treatment group consisted of fish that migrated on an individual basis or in small schools through the upstream tunnel and were trapped by study investigators via closure of the pivot door. This method of capture mirrored how the gear would be operated in a commercial setting given the current status of fish trap engineering.

Any fish that remained in the spiller compartment at the conclusion of fishing trials were cleared from the fish trap to a live well via the line-and-pulley system, representing the prototype treatment group. With all fish transferred to a live well, the spiller was then hoisted out of the water column to a suspended position to enable fish passage from the heart. This procedure mirrored that of the commercial trapping process in 2017 (Tuohy et al. 2019). However, it must be noted that modifications to the spiller compartment (specifically, addition of the upstream tunnel) affected the ability of investigators to properly operate the line-and-pulley winch system relative to the 2017 study. Furthermore, there were other subtle differences in lifting mechanics and operations due to changing personnel.

To remain consistent and enable comparison with prior alternative gear analyses (Tuohy et al. 2019), the control group consisted of fish that were passively corralled at the project site. Free-swimming fish that were unexposed to potentially damaging commercial treatment processes were sourced on an individual basis with a rubberized dip net, enabling investigators to handle, PIT-tag, and release adult fish for detection upriver in a low-impact manner. This control sourcing technique was similar to but likely less stressful than procedures used in Columbia River purse-seine, beach-seine, and tangle-net studies, during which control group fish were trapped at the Bonneville Dam adult fish passage facility, dipnetted, PIT-tagged, trucked downriver to the test fishing location (~rkm 225), and transferred from a truck into the water to repeat the upriver migration for a second time (Ashbrook 2008; WDFW 2014). Consequently, survival in our study is likely biased low relative to past studies.

It must be noted that during the May–July study period, wild and hatchery-origin spring/summer-run Chinook Salmon were captured and PIT-tagged. However, a poor return of the species to the Columbia River basin compromised the sample, resulting in inadequate precision and accuracy of Chinook Salmon survival estimates (Tuohy et al. 2020). Although fall Chinook Salmon were captured during commercial trials to potentially supplement the spring/summer Chinook Salmon sample, PIT tagging was not conducted due to concerns regarding interference with commercial harvest operations (Tuohy et al. 2020).

Sockeye Salmon mark–release–recapture analysis.— A pair of Cormack (1964) single release–recapture models was used to estimate the survival of treatment Sockeye Salmon relative to the control group ($\tau = S_{Treatment}/S_{Control}$) in upriver reaches between the fish trap site (rkm 67), Bonneville Dam (rkm 234), The Dalles Dam (rkm 309), and McNary Dam (rkm 470) on the Columbia River (Figure 4). The joint probability of survival and detection to upper basin detection sites above McNary Dam was also estimated.

The joint likelihood model for the tag analysis was described in detail by Tuohy et al. (2019) and was referred to as the complete capture history protocol by Burnham et al. (1987:112–125). With four upstream detection sites, each control or treatment release produced $2^4 = 16$ unique capture histories described in their respective likelihoods. Reach survival of the control group was parameterized by S_i ($i = 1, \ldots, 3$), whereas reach survival of treatment groups was parameterized by $S_i \times \tau_i$ ($i = 1, \ldots, 3$) in the joint likelihood model. In so doing, near- and far-field effects of the fish trap on survival of trapped and released Sockeye Salmon (τ_i) could be directly estimated from the model ($\tau_i = S_{i.Treatment}/S_{i.Control}$). Immediate survival ($\tau_0$) from capture to the time of release from the gear was observed directly. Cumulative relative survival from release to McNary Dam was estimated as $\tau_0 \times \tau_1 \times \tau_2 \times \tau_3$.

Detection histories for control and treatment groups were downloaded from the Columbia Basin PIT Tag Information System, which is operated by the Pacific States Marine Fisheries Commission and provides public access to all PIT tag detection data throughout the Columbia River basin. The tagging data were uploaded to Program USER (Lady and Skalski 2009) to calculate maximum likelihood estimates of survival as described by Skalski and Millspaugh (2006). Likelihood ratio tests were performed to identify the most parsimonious models for describing the capture process at $\alpha = 0.05$ (two-tailed).

Coho Salmon holding experimental design.— For Coho Salmon, we performed a net-pen holding study similar to those conducted by Buchanan et al. (2002) and Takata and Johnson (2018). Due to the migratory nature of Coho Salmon (which tend to spawn below main-stem Columbia River dams) and the limited PIT tag detection capabilities below Bonneville Dam, paired release–recapture has typically been ineffective in the absence of a very large sample size (WDFW 2014). As a result, Coho Salmon survival from prior alternative gear investigations has been directly estimated via net-pen holding in the lower Columbia River (Takata and Johnson 2018). This holding study was therefore performed to provide data that were comparable

FIGURE 4. Sockeye Salmon relative survival was estimated in river reaches between the Columbia River trap site (rkm 67) and Bonneville Dam (τ_1; rkm 234), The Dalles Dam (τ_2; rkm 309), and McNary Dam (τ_3; rkm 470). [Color figure can be viewed at afsjournals.org.]

to those from past studies while supplementing the Sockeye Salmon release–recapture study.

During August–October, commercial fishing trials took place at the experimental trap to evaluate the performance of the gear in a commercial selective harvest setting. At the completion of a fishing week, adult Coho Salmon (>47 cm FL) that were randomly captured at the trap through the modified commercial treatment process were transferred one by one to a temporary holding chamber of the live well until a sample of approximately 20 fish was retained. In this sample collection process, it was necessary to use a rubberized dip net to clear the fish over a small-mesh barrier (extending ~15 cm above water surface level) to the temporary holding chamber of the live well; we assumed that the rubberized net and brief moment of air exposure had no impact on fish survival. With the desired sample size achieved after a 4–8-h collection period, investigators sealed the outlets to all spiller tunnels. Coho Salmon were once again enumerated, identified by origin (adipose fin clipped or unclipped), noted for capture condition ("lively," "lethargic," or "no signs of life"), and released from the live well by hand to the sealed spiller compartment (now functioning as a net-pen holding chamber, with dimensions roughly equivalent to those specified by Takata and Johnson 2018). Once the last fish was placed into the spiller compartment, investigators initiated a 48-h observation period and noted the date, time, water temperature (°C; Extech), and presence of marine mammals. For collection of all 48-h holding samples, trap operators randomly selected the first ~20 adult Coho Salmon that passively migrated into the live well from the spiller. As in prior studies conducted by Takata and Johnson (2018), Coho Salmon that exhibited prior injuries unrelated to the commercial gear were excluded from the holding study.

Coho Salmon holding analysis.— Postrelease survival of Coho Salmon captured with the modified commercial fish trap was estimated by holding and observing six treatment groups of fish for a 48-h period in a net-pen providing about 90.62 m^3 (3,200 ft^3) of holding space (depending on tide height). To determine fish mortalities during the holding period, treatment groups were checked twice daily at regular intervals from above and below the water surface (via snorkel survey). At the end of the 48-h holding period, all fish were cleared from the holding pen to a live well via the 2017 prototype line-and-pulley method (Tuohy et al. 2019). These fish were then enumerated, measured (FL), scanned for PIT tags, identified for species type and origin (hatchery or wild), noted for condition, and released. Postrelease survival was directly estimated by a binomial proportion ($p =$ number that survived/total number) with associated binomial variance. In the case of no observed mortality, a lower one-tailed interval estimate of survival was calculated using the method of Skalski (1981). As in prior lower Columbia River holding studies, the effects of confinement on Coho Salmon were not controlled (Takata and Johnson 2018).

RESULTS

Total Catch

The experimental trap was fished over a 40-d period between May 5 and July 3, 2019, and over a 46-d period between August 19 and October 30, 2019. In total, 6,278 adult and jack salmonids were captured. Nonjuvenile catch comprised 64.1% Coho Salmon (4,024 total; 62.9% adipose clipped; 12.4% jack salmon [<47 cm]), 12.1% Chinook Salmon (758 total; 56.3% adipose clipped; 23.4% jack salmon [<57 cm]), 14.3% Sockeye Salmon (896 total; 0.00% adipose clipped), 9.0% summer steelhead (568 total; 70.8% adipose clipped), 0.08% Chum Salmon (5 total; 0.0% adipose clipped), 0.03% Pink Salmon *O. gorbuscha* (2 total; 0.0% adipose clipped), 0.19% resident/residualized (<30-cm) Rainbow Trout (12 total; 54.5% adipose clipped), 0.19% resident (<30-cm) Cutthroat Trout *O. clarkii* (12 total; 0.0% adipose clipped), and 0.02% unidentified salmonid (1 total).

In addition to salmonid catch, we captured 357 American Shad *Alosa sapidissima*, 80 Largescale Sucker *Catostomus macrocheilus*, 36 Northern Pikeminnow *Ptychocheilus oregonensis*, 16 Starry Flounder *Platichthys stellatus*, 11 Peamouth *Mylocheilus caurinus*, 2 White Sturgeon *Acipenser transmontanus*, 2 Pacific Lamprey *Entosphenus tridentatus*, 1 Largemouth Bass *Micropterus salmoides*, and 1 Common Carp *Cyprinus carpio*.

During the study, immediate mortalities occurred for a total of 5 Sockeye Salmon (<400 mm FL), 5 Coho Salmon jacks (<400 mm FL), and 253 juvenile Chinook Salmon smolts (150–250 mm FL; 91% adipose clipped). All immediate mortalities of salmonids occurred from wedging or gilling in relatively confined spaces of the trap. Juvenile Chinook Salmon were impacted by 3.81–6.35-cm stretch mesh in the spiller and live well; small-bodied Sockeye Salmon and Coho Salmon jacks (<400 mm FL) were predominantly impacted by a small panel of 7.94-cm stretch mesh deployed at the intersection of the heart and the jigger.

Survival of Sockeye Salmon

Sockeye Salmon were first encountered at the trap on May 28 and remained abundant when fishing ceased on July 3, 2019. Water temperatures during this study period ranged from 14.4°C to 19.2°C (mean = 17.0°C). Of the 896 Sockeye Salmon that were captured, a total of 402 control, 309 modified treatment, and 138 prototype treatment Sockeye Salmon were PIT-tagged in nearly equal cumulative proportions throughout the study (Figure 5).

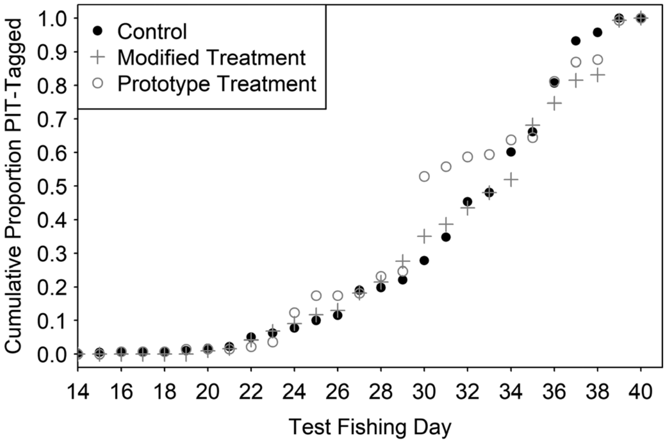

FIGURE 5. Sockeye Salmon were randomly captured, PIT-tagged, and assigned so that each treatment and control group was represented throughout the study period in nearly equal cumulative proportions. This sampling and assignment effort reduced the likelihood that model assumptions of homogeneous tagging conditions would be violated.

Over the course of research and commercial trials, five immediate mortalities occurred (all < 400 mm FL), resulting in an immediate survival rate ($\hat{\tau}_0$) of 0.994 ($\widehat{SE}$ = 0.002) for Sockeye Salmon (Table 1).

Likelihood ratio tests found no significant difference in PIT tag array detection probabilities for control and modified treatment groups ($\chi^2_3 \geq 5.543$, $P = 0.136$), resulting in the selection of a reduced model with a common detection probability for control and treatment fish by location. Postrelease survival for the modified treatment group compared to the control group from their release at the trap to Bonneville Dam ($\hat{\tau}_1$) was 0.983 ($\widehat{SE}$ = 0.021; Table 1). The survival rate of the treatment group was higher than that of the control group between Bonneville and The Dalles dams, with relative survival ($\hat{\tau}_2$) estimated at 1.008 ($\widehat{SE}$ = 0.016); and between The Dalles and McNary dams, with relative survival ($\hat{\tau}_3$) estimated at 1.033 ($\widehat{SE}$ = 0.019). Cumulative relative survival ($\tau_0 \times \tau_1 \times \tau_2 \times \tau_3$) for the modified treatment group from capture at the trap site to McNary Dam (~400 km upstream; 8-d median travel duration) was estimated to be 1.017 ($\widehat{SE}$ = 0.032; Table 1).

Between May 28 and July 3, a total of 32 spiller hauls were performed with the prototype treatment design, of which only 21 hauls resulted in the capture of Sockeye Salmon. Likelihood ratio tests found no significant difference in PIT tag array detection probabilities for control and prototype treatment groups ($\chi^2_3 \geq 2.864$, $P = 0.413$), resulting in the selection of a reduced model with a common detection probability for the fish at a location. Short-term relative postrelease survival from the gear to Bonneville Dam ($\hat{\tau}_1$) was estimated at 0.796 ($\widehat{SE}$ = 0.041; Table 1). Between Bonneville and The Dalles dams, survival was nearly equivalent to that of the control group, with $\hat{\tau}_2 = 1.004$ ($\widehat{SE}$ = 0.024). Relative survival remained high in the final reach between The Dalles and McNary dams, with $\hat{\tau}_3$ equal to 0.974 ($\widehat{SE}$ = 0.035). Nevertheless, survival of Sockeye Salmon that were exposed to the prototype treatment was significantly different from the survival of those exposed to the modified fish trap treatment ($|Z| \geq 4.963$, $P < 0.001$; Table 1), with cumulative relative survival from release to McNary Dam estimated at 0.774 ($\widehat{SE}$ = 0.051).

Survival of Coho Salmon

The Coho Salmon holding study was conducted between September 27 and October 30, 2019. During this study period, water temperatures ranged from 12.1°C to 19.2°C (mean = 15.79°C). Encountering 3,523 adult Coho Salmon at the trap site over the course of the study, there were zero immediate mortalities of adult Coho Salmon, resulting in an immediate survival rate $\hat{S}$ of 1.000 (lower 95% confidence limit: $S \geq 0.999$). In total, 121 Coho Salmon were held in captivity after release from the commercial gear in six separate subsample groups (Table 2). Zero mortalities occurred during the 48-h holding period, resulting in a postrelease survival estimate $\hat{S}$ of 1.000 (lower 95% confidence limit: $S \geq 0.978$). All Coho Salmon that were encountered during the fish collection process for the holding study were lively and vigorous upon capture and release after 48 h, and no fish appeared lethargic or asphyxiated.

DISCUSSION

Bycatch Survival

Through two distinct research approaches, this study has demonstrated the potential of a modified commercial trapping technique to achieve essentially 100% survival of adult salmonid bycatch. Estimated relative survival ($\tau_0 \times \tau_1 \times \tau_2 \times \tau_3$) of Sockeye Salmon from the modified trap design using a paired release–recapture study was 1.017 (95% CI: 0.974 $\leq \hat{\tau}_{cumulative} \leq$ 1.059) over a 400-km migration to McNary Dam. Utilizing an alternative 48-h net-pen holding approach, survival of Coho Salmon was directly estimated at 1.000 (lower 95% confidence limit: $S \geq 0.978$). Regardless of the estimation technique employed, the modified passive capture design, which mostly eliminated air exposure and net contact and also minimized handling and crowding, had no detectable impact on salmon release survival. Despite the limitations of a single-year data set, these results suggest that fish trapping could significantly reduce salmonid bycatch mortality if applied in terminal commercial salmon fisheries (Table 3).

Relative to the performance of the prototype fish trap used in 2017, results from the modified fish trap design

TABLE 1. Relative treatment effect (i.e., $\tau = S_{Treatment}/S_{Control}$) on postrelease survival for Sockeye Salmon encountered at the trap in Cathlamet Channel, Columbia River. The 95% profile likelihood confidence intervals (in parentheses) were estimated by river reach for the modified commercial treatment and the prototype commercial treatment; *P*-values for two-tailed tests of equal survival are reported. Immediate survival (τ_0) was set equal between treatment groups, as all immediate mortalities resulted from processes that were shared by the two capture treatments.

River reach	Modified treatment survival point estimate	Prototype treatment survival point estimate	*P*-value
Immediate survival (τ_0)	0.994 (0.988–0.998)	0.994 (0.988–0.998)	
Gear to Bonneville Dam (τ_1)	0.983 (0.942–1.024)	0.796 (0.712–0.872)	<0.001
Bonneville Dam to The Dalles Dam (τ_2)	1.008 (0.974–1.041)	1.004 (0.948–1.045)	0.861
The Dalles Dam to McNary Dam (τ_3)	1.033 (0.995–1.072)	0.974 (0.899–1.033)	0.034
Cumulative ($\tau_0 \times \tau_1 \times \tau_2 \times \tau_3$)	1.017 (0.974–1.059)	0.774 (0.673–0.872)	<0.001

TABLE 2. Subsamples of Coho Salmon that were captured with the modified fish trap in Cathlamet Channel, Columbia River, were held for a 48-h period to directly estimate release survival; water quality conditions were recorded. Mean water temperature is presented with 95% CI in parentheses.

Subsample number	Date	Mean water temperature (°C)	Coho Salmon sample size	Number that survived	Coho Salmon survival
1	Sep 27–29	18.77 (18.69–18.85)	13	13	1.000
2	Sep 30–Oct 2	17.74 (17.64–17.84)	27	27	1.000
3	Oct 3–5	16.31 (16.24–16.39)	34	34	1.000
4	Oct 10–12	15.63 (15.53–15.74)	13	13	1.000
5	Oct 23–25	13.57 (13.50–13.65)	24	24	1.000
6	Oct 28–30	12.75 (12.64–12.85)	10	10	1.000
Total			121	121	1.000

TABLE 3. Comparison of cumulative survival estimates (with associated 95% CIs [in parentheses] if available) for salmonids by gear type. If lower Columbia River data were not available for comparison, lower Fraser River data were used.

Gear	Chinook Salmon survival	Coho Salmon survival	Sockeye Salmon survival	Steelhead survival
Gill net	0.520[a]	0.400[e]	0.400[e]	0.552[h]
Tangle net	0.764[b]	0.764[f]	0.900[e]	0.764[f]
Beach seine	0.750 (0.710–0.790)[c]	0.620[g]	0.950[e]	0.920 (0.820–1.000)[c]
Purse seine	0.780 (0.720–0.850)[c]	0.710[g]	0.900[e]	0.980 (0.930–1.000)[c]
Fish trap	0.995 (0.924–1.071)[d]	1.000 (0.978–1.000)	1.017 (0.974–1.059)	0.944 (0.880–1.012)[d]

[a] Independent Fisheries Science Panel (2014).
[b] TAC (2018).
[c] WDFW (2014).
[d] Tuohy et al. (2019).
[e] CDFO (2017).
[f] ODFW and WDFW (2018).
[g] TAC (2015).
[h] TAC (2008).

represent an improvement that warrants incorporation into all future commercial salmon traps. Although results from this 2019 study for Sockeye Salmon and Coho Salmon cannot be directly compared with and extrapolated to other species or other periods of study, it is highly likely that the modified passive capture design would achieve improved survival results for Chinook Salmon and steelhead if tested. In 2017, cumulative survival over 400 km to McNary Dam from the prototype trap design was estimated at 0.944 (95% CI: $0.880 \leq \hat{\tau}_{cumulative} \leq 1.012$) for steelhead and 0.995 (95% CI: $0.924 \leq \hat{\tau}_{cumulative} \leq 1.071$) for Chinook Salmon through an equivalent mark–recapture methodology (Tuohy et al. 2019). Further research is warranted to investigate potential improvements in survival for these species from recent engineering advancements in fish trap technology.

Analyzing differences between Sockeye Salmon survival estimates from the two trap designs (modified treatment and prototype treatment) in 2019, the older prototype trapping method demonstrated a surprisingly deleterious and significant effect on Sockeye Salmon survival relative to the new modified passive trapping method (Table 1). The cause of this poor performance relative to the 2017 results for Chinook Salmon and steelhead exposed to the prototype treatment remains unknown; however, the relatively poor performance may be attributable to several factors, including the scarcity of hauls performed, addition of the upstream tunnel for passive capture, annual differences in lifting mechanics, operator error, or water quality conditions. With significantly fewer hauls performed in 2019 by using the prototype method ($N_{2017} = 381$; $N_{2019} = 32$), operators had less opportunity to learn from their mistakes and adjust spiller mechanics. It was noted on multiple occasions that spills were poorly performed during the spring season study (often due to the presence of the upstream tunnel for passive capture), potentially causing physiological stress to captured fish. Investigating the prototype treatment data set, results were heavily skewed by four major spill events (>10 Sockeye Salmon spilled and tagged) and one significant outlier in which relative release survival was only 0.093 (likely due to operator error). This result (1) highlights the need for skilled and attentive operators if the line-and-pulley prototype technique of 2017 is employed and (2) lends support for the modified passive capture design, which dramatically reduces the likelihood of potential operator error and significantly improves the release survival of fish (Table 1). Differences in water quality conditions could also affect survival between years and seasons of study, with warmer water temperatures generally reducing the survival of captured and released salmonids (Crossin et al. 2008; Gale et al. 2013; Raby et al. 2015). Nevertheless, the Sockeye Salmon results for the prototype design in 2019 should perhaps be taken lightly given the small sample size available for analysis (i.e., 138 fish), the scarcity of hauls performed (i.e., 32), flaws in spiller operations, and the obsolescence of the prototype method of capture.

Management Recommendations

Bycatch impacts vary in relation to commercial gear types, users and designs of a specific gear type, localized environmental factors, and biological factors (Raby et al. 2015; Teffer et al. 2017; Bass et al. 2018). This variance is a challenge to management of all fisheries and gear types (CDFO 2017). As resource managers in the U.S. Pacific Northwest consider commercial or research application of fish traps in fluvial settings, regulations specific to trap design and operation should be carefully considered to optimize performance and maximize conservation benefits. Recent engineering advancements have demonstrated promise for dramatically reducing salmonid bycatch mortality and expanding sustainable fishing opportunities in fluvial settings similar to the lower Columbia River (Table 2). However, as is the case for all commercial gears, not all trap designs, operations, and their impacts to salmonid survival appear equal.

We recommend that trap designs approved for future operation be heavily regulated, with operators certified to achieve maximum conservation benefit. First, fish traps must be researched and tested if deployed in a new regional environment to ensure compatibility with the ecosystem. Investigators or fishers must consider the ecology of aquatic fish, invertebrate, and marine mammal species at all life history stages during site selection and engineering processes. Specifics such as mesh size and material, depth, location, marine mammal deterrence methods, lead length, heart configuration, and spiller design should be carefully considered and regulated by management within a watershed to maximize benefits and minimize potential harm to the ecosystem (e.g., bycatch mortality, enhanced marine mammal predation, or delayed fish migration timing; Tuohy et al. 2020). Spiller mechanics should be based on this 2019 design, operating as passively as possible to minimize bycatch impacts and the likelihood of operator error while being managed according to a design's unique performance record. Operators in any fishery must be privy to fish identification for selective harvest and passive release of bycatch, causing minimal harassment to nontarget stocks. To ensure compliance with fishery-specific regulations and achieve desired conservation outcomes, electronic monitoring systems are recommended for use at each fish trap site (Tuohy et al. 2020). Depending on the turbidity conditions encountered within a fishery, underwater video cameras could be employed within each live well for stock composition and regulatory compliance monitoring.

If regulated and managed appropriately in a watershed to meet the biological needs of unique salmonid populations (Gayeski et al. 2018b), modified fish traps have the potential to dramatically reduce bycatch mortality of ESA-listed salmonids, maintain the age and size structure of harvested fish populations (Ricker 1981; Lewis et al. 2015), alleviate commercial fishery constraints, increase selective fishing opportunity for robust or hatchery-origin fish stocks, and improve the quality of harvested seafood products. Trap fisheries operating in-river do not deprive southern resident killer whales *Orcinus orca* of marine food resources (Ford et al. 2010; Lacy et al. 2017). Benefiting wild salmon recovery and preserving a key trophic link for killer whales, the gear could be certified sustainable in the marketplace and branded for both quality and sustainability to improve prospects for fishers and depressed coastal fishing communities of the region (Johnson 2018; Gayeski et al. 2018a). Commercial fishing operations could be paired with low-impact data collection by resource management agencies at trap sites to better understand fish behavior and ecology (Link and English 2000). Although further research of the gear is necessary (e.g., new river locations, modified designs, potential fish migration delay effects, marine mammal interactions, electronic monitoring applications, and economic viability), results of this study show that modified fish traps have the potential to significantly reduce salmonid bycatch mortality for the benefit of the commercial fishing industry, fisheries management, wild salmonid conservation, and the environment.

ACKNOWLEDGMENTS

This project was made possible by funding received from the National Oceanic and Atmospheric Administration Fisheries Service (awards NA17NMF4720255 and NA19NMF4270028) in cooperation with the Bycatch Reduction Engineering Program and the Saltonstall–Kennedy Grant Program. Additional support was provided by the Washington Department of Fish and Wildlife and by Patagonia, Inc. We thank the many people who collaborated and contributed to the study to make it a success: Kurt Beardslee, Jamie Glasgow, Joe Verrelli, Blake Joplin, Danielle Dorsch, Billie Delaney, and Brennan Helwig (Wild Fish Conservancy); Lisa Harlan, Ryan Lothrop, and Bill Tweit (Washington Department of Fish and Wildlife); commercial fisherman Jon Blair Peterson; fish buyer and processor Mike Clark (C&H Classic Smoked Fish); Seattle chef Renee Erickson (Sea Creatures); Shane Anderson (North Fork Studios); Wild Salmon Center; and the University of Washington School of Aquatic and Fishery Sciences for faculty review. All data may be downloaded free of charge through the Wild Fish Conservancy Web page (www.wildfishconservancy.org) by clicking on the “Projects” and “Columbia River Pound Net Project” tabs. All PIT tag information can be accessed through the Columbia Basin PIT Tag Information System Web page (www.ptagis.com) using the code “CPN” and name “Cathlamet Pound Net.” There is no conflict of interest declared in this article.

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