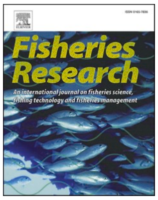
Fisheries Research 257 (2023) 106495

Contents lists available at ScienceDirect

Fisheries Research

journal homepage: www.elsevier.com/locate/fishres



Maximizing salmonid bycatch survival with passively operated commercial fish traps

Adrian M. Tuohy [a,*], Aaron T. Jorgenson [a], John R. Skalski [b]

[a] Wild Fish Conservancy, 15629 Main St NE, Duvall, WA 98019, USA
[b] Columbia Basin Research, School of Aquatic and Fishery Sciences, University of Washington, 1325 4th Avenue, Suite 1515, Seattle, WA 98101, USA

ARTICLE INFO

Handled by A.E. Punt

Keywords:
Fish trap
Pound net
Salmon
Bycatch
Survival
Mortality

ABSTRACT

Commercial fish traps were recently implemented at a limited scale in the lower Columbia River in efforts to selectively harvest hatchery-origin fishes with minimal mortality of wild-origin salmonids listed under the U.S. Endangered Species Act. Prior studies of a modified passive trapping technique demonstrated nearly 100 % survival among adult salmonids released as bycatch. Building upon this research, additional survival studies for adult coho salmon, spring-run Chinook salmon, and summer-run Chinook salmon were conducted between 2019 and 2021 at two separate fish trap sites in the lower Columbia River. Over three years of study, we used mark-recapture and net pen holding methodologies to estimate post-release survival of Chinook salmon and coho salmon, respectively. Evaluating detections of Chinook salmon tagged and released from a passively operated fish trap in 2019, detection at Bonneville Dam over a mean 6.5 d upriver migration (167 km) was 1.000 (95 % CI: $S \geq 0.970$) for the sample genetically assigned to populations originating upriver of Bonneville Dam. Through two separate net pen holding studies, post-release survival of coho salmon was estimated at 1.000 (95 % CI: $S \geq 0.975$) over 4 d in 2020 and 0.965 (95 % CI: $0.948 \leq S \leq 0.969$) over 6 d in 2021. Given that these analyses lacked control groups to adjust survival estimates for confounding mortality effects, study results are inherently conservative. Ultimately, the findings of our research support the conclusions of prior studies and further suggest that passively operated fish traps may allow for selective harvesting of targeted fish stocks with little to no mortality of adult salmonid bycatch.

1. Introduction

Bycatch and mixed-stock harvesting of Endangered Species Act (ESA)-listed Pacific Salmonids (*Oncorhynchus Spp.)* constrains fishing opportunities for abundant hatchery-origin fishes and impacts wild-origin salmonid populations throughout the U.S. Pacific Northwest (NRC, 1996; WDFW, 1997; Anderson et al., 2020). Mostly to the detriment of wild salmonid population genetics and ecosystems (Naish et al., 2007), millions of hatchery fish are produced annually from federal, state, and tribal hatcheries to increase short-term fishing opportunities (Mahnken et al., 1998; Utter and Epifanio, 2002). However, absent fishing practices that can selectively harvest hatchery-origin fishes while releasing ESA-listed wild-origin salmonids unharmed, neither hatcheries nor salmon fisheries can be managed effectively to achieve conservation or harvest objectives (HSRG, 2009; Gayeski et al., 2018). In the Columbia River, this management paradigm of production hatcheries and mixed-stock harvesting contributed to the decline and extirpation of wild salmonid populations (Cramer et al., 1991; NRC, 1996; Lichatowich, 1999). Although efforts have been made to reform both harvest and hatchery management (WFWC, 2009, 2013; US v. OR MA, 2018), it is evident that these same management factors continue to limit the recovery of wild-origin salmonids (Lichatowich et al., 2017; Anderson et al., 2020). For example, the proportion of hatchery-origin spawners consistently exceeds biological targets designed to protect wild salmonid population fitness throughout the basin (HSRG, 2009; WDFW, 2022). Furthermore, mixed-stock harvesting with gill nets continues to impact ESA-listed fishes and severely constrain fishing opportunities to remove hatchery-origin fish that have been produced for the purpose of increasing short-term harvest opportunities (ODFW and WDFW, 2020). Clearly, management goals for wild salmonid conservation, hatchery reform, and harvest reform are not being achieved through the existing salmon management paradigm and not one of thirteen ESA-listed salmonid populations groups have recovered (NWFSC, 2015; Gayeski et al., 2018; WDFW, 2018).

---

* Correspondence to: Wild Fish Conservancy, PO Box 402, Duvall, WA 98019, USA.
E-mail address: adrian@wildfishconservancy.org (A.M. Tuohy).

https://doi.org/10.1016/j.fishres.2022.106495
Received 2 June 2022; Received in revised form 6 September 2022; Accepted 7 September 2022

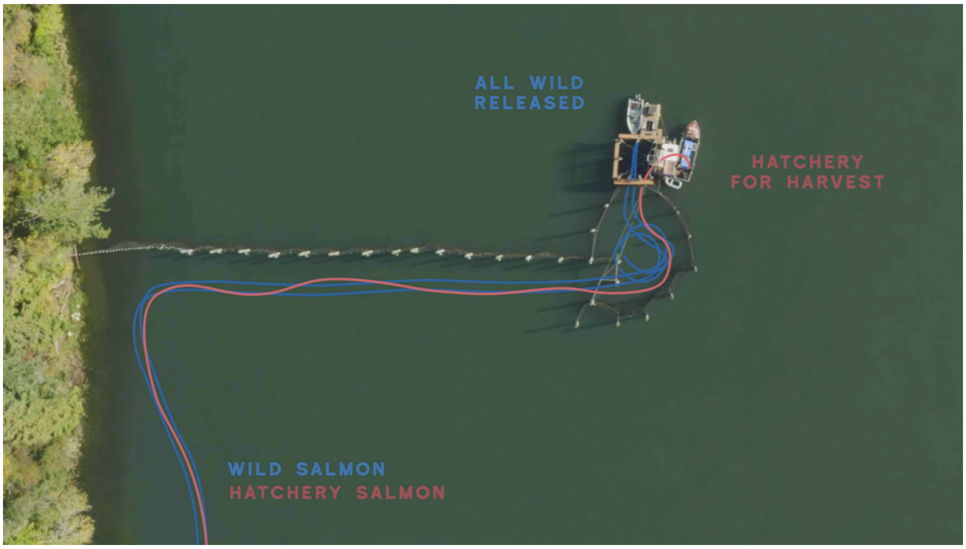
In efforts to increase harvest opportunities for hatchery-origin fishes and improve survival of wild-origin salmonids, fish and wildlife commissioners of Washington and Oregon directed resource managers to develop and implement low-impact selective alternatives to conventional gill netting in the Columbia River and elsewhere throughout the region (WFWC, 2009, 2013, 2015; ODFW, 2013). Alternative gears—including beach seines, modified purse seines, and tangle nets—were tested between 2001 and 2016 in the lower Columbia River to estimate bycatch mortality rates and bycatch encounters for comparison to that of the conventional gill net (Vander Haegen et al., 2004; WDFW, 2014; Takata and Johnson, 2018). Gill nets were studied for post-release bycatch mortality effects to spring Chinook salmon (*Oncorhynchus tshawytscha*) (Vander Haegen et al., 2004), however, no data were collected for estimation of gill net post-release mortality impacts to other critical bycatch stocks in primary commercial fisheries (NMFS, 2018). Due in part to apparent bycatch impact limitations of studied alternative gears in fall season fisheries, amongst other factors, state policy directives to develop and implement alternative gears while phasing out gill nets in the mainstem Columbia River did not materialize (WDFW, 2018).

In 2016, the nonprofit organization Wild Fish Conservancy (WFC) and a local commercial fisher constructed the first operational fish trap (or, "pound net") in over 80 years since the ban of fixed-gear fishing methods in the lower Columbia River's Cathlamet Channel (Wahkiakum County, Washington; river kilometer (rkm) 67). The gear was deployed to assess a low-impact methodology for fisheries monitoring, reduce bycatch impacts in commercial fisheries, and improve selective harvesting of hatchery-origin salmon (Tuohy, 2018; Tuohy et al., 2019).

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 in which fish rarely escape (Cobb, 1930). Salmonids encountering the lead instinctively move against the current into progressively smaller compartments of the trap ("heart," "tunnel," "pot/spiller," and "live well," respectively) (Cobb, 1930; Tuohy et al., 2019; Video 1). The final compartment has dimensions appropriate for operators to sort the catch for harvest or release with little to no air exposure and handling. Salmonids remain free-swimming within a fish trap and mesh dimensions are designed to prevent entanglement (Tuohy et al., 2019).

Similar to historical fish trap designs used in the Columbia River, the experimental fish trap installed in 2016 functioned to passively corral returning adult fishes from the lead and heart walls to an upstream-positioned pot compartment (~6 m wide x 6 m long x 6 m deep). When approximately 10–40 fishes could be observed free-swimming in the pot, the catch was quickly brailed (or, "spilled") to the shallows en masse (depth 0–1 m) using line-and-pulley and a solar-powered winch (Tuohy et al., 2019) (Video 1). After the brailing process was completed within ~20–45 s to transfer the catch to an adjacent submerged live well (depth 1 m), the fishes were hand sorted by species and adipose fin-clip status (suggesting hatchery or wild origins) with all fishes remaining underwater. Bycatch were then released by hand over the outer wall of the live well (approx. 5 cm above the water surface), exposing fish to air for ~1 s. In contrast with gill netting, these methods eliminated entanglement of adult salmonids and dramatically reduced air exposure and handling effects known to contribute to bycatch mortality (Donaldson et al., 2014; Raby et al., 2015a, 2015b). It must be further noted that free-swimming fishes passively captured in the pot prior to brailing could also be individually dip-netted into a live well for data collection and passive release through a submerged exit door to the live well. This technique was less efficient for operators but essentially eliminated potential mortality effects from air exposure and overcrowding and reduced stress during capture relative to brailing (Tuohy et al., 2019; Cox and Sippel, 2020).

To evaluate the effects of the alternative gear to bycatch, post-release survival from brailing operations with the prototype fish trap was estimated through a paired release-recapture study in 2017 using passive integrated transponder (PIT)-tags (Tuohy et al., 2019). Survival of trapped and brailed fish compared to passively released dip-netted controls over a 400-km migration to McNary Dam was estimated at 0.944 ($\widehat{SE} = 0.046$) and 0.995 ($\widehat{SE} = 0.078$) for summer-run steelhead (*Oncorhynchus mykiss*) and fall-run Chinook salmon (including both lower river tule and upriver bright populations), respectively (Tuohy et al., 2019). In a separate analysis conducted by the Washington Department of Fish and Wildlife, relative survival of fishes brailed from the fish trap compared to control groups of fishes previously tagged in the juvenile life-history stage and redetected in the lower river as adults was estimated at 0.947 (CI ($S \geq 0.724$) = 0.95) for steelhead and 0.935



Video 1. Vid. 1. An experimental fish trap in Cathlamet Channel, WA funnels returning adult salmonids from the lead wall to a sorting compartment in 2019. In the final moment of capture, the catch can be brailed or funneled passively to the sorting compartment for data collection and release, or selective harvest.A video clip is available online. Supplementary material related to this article can be found online at doi:10.1016/j.fishres.2022.106495.

(CI ($S \geq 0.648) = 0.95$)) for Chinook salmon (upriver bright populations only) (Cox and Sippel, 2020).

Research by Tuohy et al. (2019) and Cox and Sippel (2020) demonstrated high post-release survival rates for steelhead and Chinook salmon bycatch brailed from fish traps. Yet another critical finding from these studies was that fishes unexposed to brailing (e.g., those dip-netted and passively released from fish trap operations) survived at greater rates than those that were brailed. As detailed in Cox and Sippel (2020), there appeared to be no detectable impact to the survival of dip-netted and passively released steelhead and Chinook salmon and from the fish trap in 2017.

Given promising results from these early studies, efforts were made to further improve post-release survival of all captured and released fishes from the gear through development of passive capture operations and the phasing-out of brailing techniques. The fish trap design and final capture processes at the Cathlamet, WA site were modified in 2019 in efforts to eliminate fish air exposure, handling, overcrowding, and net contact previously associated with the prototype brailing process (Tuohy et al., 2020). In contrast with the earlier prototype design, the upstream-positioned pot was altered to passively funnel fishes one-by-one against the ebb current into an upstream-positioned live well without brailing en masse or necessitating a dip-net (Video 1). Using underwater video cameras or observation above the water column, the free-swimming catch could be identified within the live well to species and adipose fin-clip status, allowing for selective removal of hatchery-origin fishes and passive release of non-target fishes through a submerged exit door (Tuohy et al., 2020). This method was defined as the "passive operation."

In efforts to assess the effectiveness of fish trap modifications, post-release survival of sockeye salmon (*Oncorhynchus nerka*) and coho salmon (*Oncorhynchus kisutch*) from passive operations was estimated and compared to that of brailing operations in side-by-side studies in 2019 (Tuohy et al., 2020). Demonstrating significant improvements in bycatch survival and 100 % post-release survival for both sockeye salmon and coho salmon (Tuohy et al., 2020), passive operations were expanded to allow for effective capture during all tides with construction of a double-ended fish trap in Clifton Channel, OR in 2021 (Video 2). This modified trap was designed to fully eliminate the brailing technique from fishing operations.

Although data from prior studies has indicated that passive operations with fish traps may have little to no effect to released salmonid bycatch (Tuohy et al., 2020; Cox and Sippel, 2020), bycatch survival rates are known to vary depending on the species encountered, the timing of seasonal gear operation, and water quality conditions (among other factors) (Davis, 2002; Raby et al., 2015a, 2015b). For these reasons, stock-specific post-release survival studies and data collection have been encouraged by fisheries management agencies for most commercial gears that may impact ESA-listed species within a specific season in the Columbia River. Therefore, we conducted additional studies of two passively operated fish traps between 2019 and 2021 to further evaluate bycatch survival rates for coho salmon and fill existing data gaps for spring-run and summer-run Chinook salmon in the lower Columbia River. We hypothesized that survival estimates for passive operations with fish traps would continue to exceed that of brailing operations from the prototype fish trap design, nearing 100 %. Given that wild populations of spring-run Chinook salmon and coho salmon are listed under the ESA (constraining or impeding commercial gill net and alternative gear fisheries in the Columbia River), accurate and precise estimates of bycatch impacts are paramount to fisheries management and the recovery of these ESA-listed species (NMFS, 2018). Bycatch survival results for both Chinook salmon and coho salmon are presented together within this publication to ensure peer-review and summary of the outlying data from our fish trap studies conducted on the lower Columbia River.

2. Materials and methods

2.1. Study location

Two fish traps were studied between 2019 and 2021 in the lower Columbia River where fish traps were commonly used prior to a ban of fixed fishing gear in Washington State and Oregon in 1934 and 1948, respectively (Fig. 1) (Washington State Session Laws, 1935; State of Oregon, 1948). In 2019–2020, pilot research of passive capture operations occurred at rkm 67 on the lower Columbia River in the Cathlamet Channel (Wahkiakum County, Washington). This trap occupied the same location as used in the studies of Tuohy et al. (2020). In 2021, research of passive capture operations occurred at a new site near rkm 55 in the Clifton Channel (Clatsop County, Oregon) (Fig. 1). At these locations, the maximum depth at high-tide toward the riverward-end of

Video 2. Vid. 2. A modified fish trap in Clifton Channel, OR operates to capture and release salmonids passively during all tidal stages in 2021.A video clip is available online. Supplementary material related to this article can be found online at doi:10.1016/j.fishres.2022.106495.

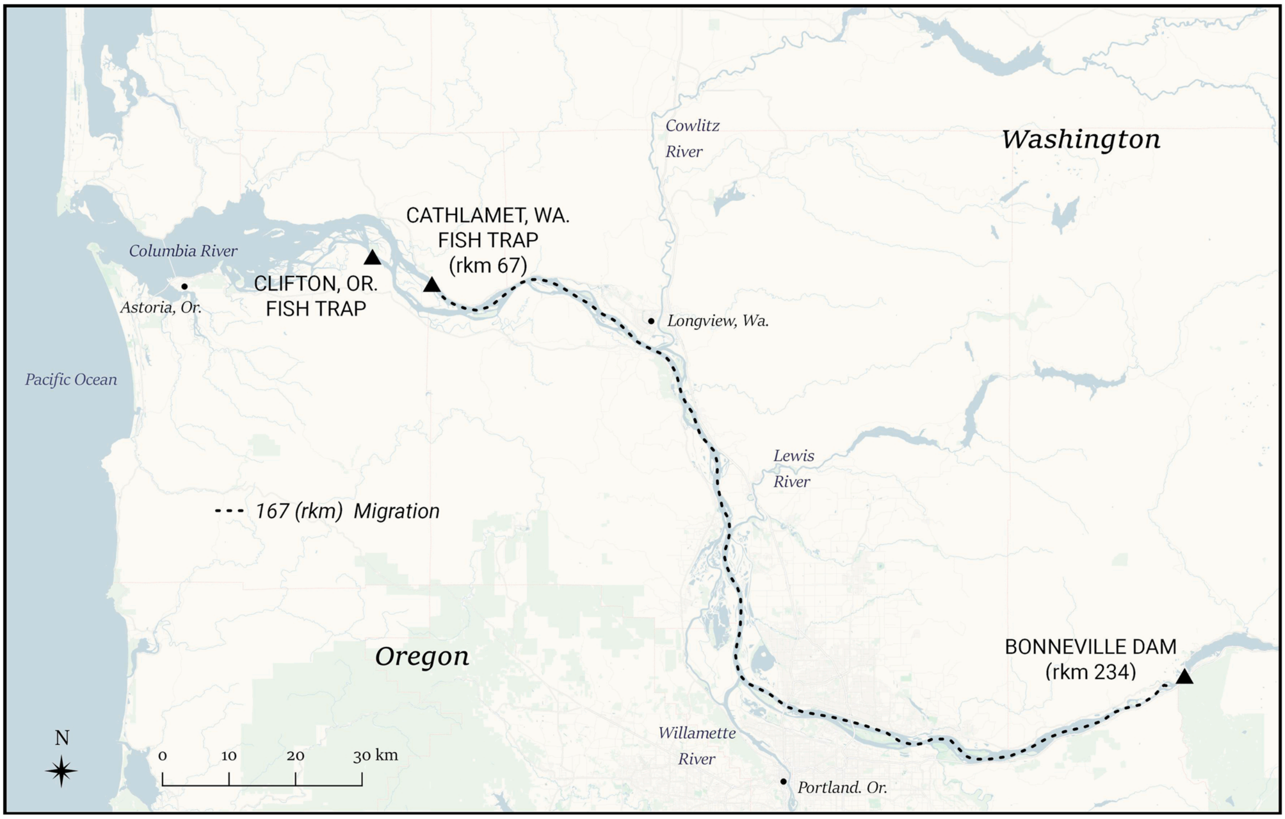


Fig. 1. Research occurred at two fish trap sites in the lower Columbia River: (1) Cathlamet, WA (rkm 67); and (2) Clifton, OR (rkm 55). Mark-recapture research evaluated Chinook salmon survival from the Cathlamet, WA fish trap to Bonneville Dam (rkm 234) located 167 km upriver. [Intended for color reproduction].

the trap ranged from 6 m to 9 m. Daily tidal flux ranged from 1.5 m to 2.8 m.

2.2. Fish trap design

For studies of spring-run and summer-run Chinook salmon survival in 2019, the Cathlamet Channel fish trap (Fig. 2a) was used to evaluate potential survival benefits of passive capture operations relative to prototype brailing operations (similar to concurrent studies by Tuohy et al., 2020 for sockeye salmon). As described in detail within Tuohy et al. (2020), this fish trap consisted of a lead (~90 m; 7.94 cm stretch mesh), jigger (~10 m; 7.94 cm stretch mesh), and heart (23-m length; 20-m maximum width; 6.35 cm stretch mesh) (Christensen Net Works, Everson, Washington). It was equipped with one pot (6 × 6 × 9 m; 6.35 cm stretch mesh) and two live wells (2.74 × 0.61 × 0.76 m) (Fig. 2a): one attached at the upstream side of the heart compartment (allowing for effective passive capture during ebb tides), and the other positioned riverward to retain the ability of the prototype fish trap design to brail fishes (Tuohy et al., 2019). This multi-operational fish trap allowed for pilot studies of passive operations and side-by-side

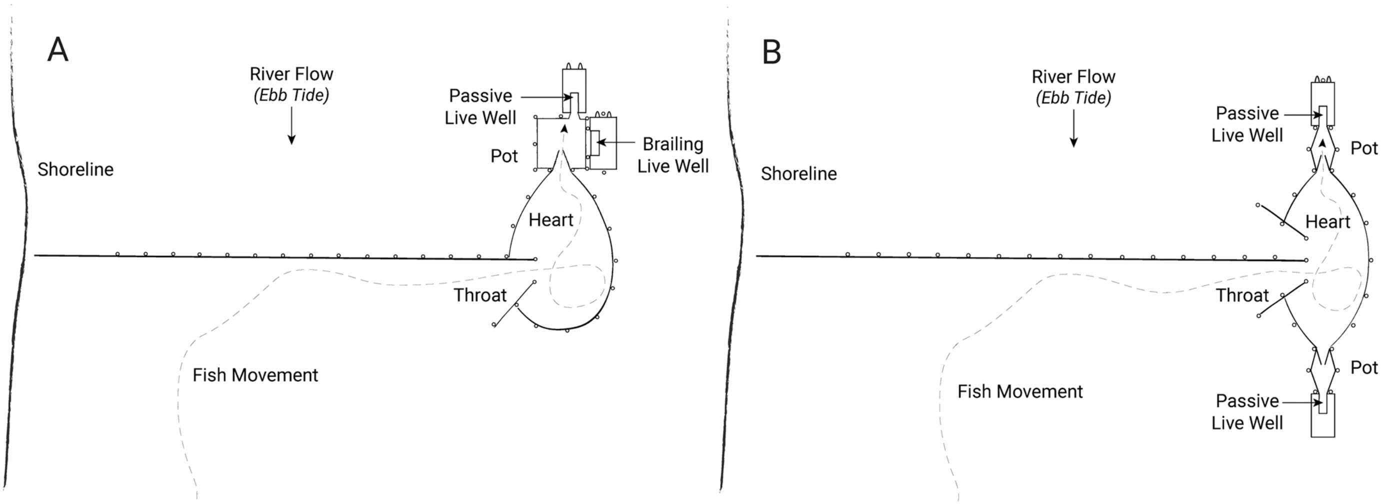


Fig. 2. Bycatch survival was evaluated at two separate fish trap sites. The Cathlamet, WA fish trap (A) was equipped with only one pot, from which fishes could be passively captured on the ebb tide or brailed in order to compare bycatch post-release survival effects from each treatment. The Clifton, OR fish trap (B) was equipped with two pots to allow for passive capture operations during all tides.

comparison to prototype brailing operations (Fig. 2a). Beyond survival investigations for spring-run and summer run Chinook salmon, this trap was further used for study of coho salmon survival, specifically for passive operations in 2020.

For studies of coho salmon in 2021, the Clifton Channel fish trap was used to estimate survival from passive operations. This fish trap was similar in design to that described by Tuohy et al. (2020), consisting of a lead (~90 m; 7.94 cm stretch mesh), jigger (~10 m; 6.35 cm stretch mesh), and heart (27-m length; 20-m maximum width; 6.35 cm stretch mesh) (Christensen Net Works, Everson, Washington) (Fig. 2b). The design embraced the same passive capture operation piloted by Tuohy et al. (2020) during the final moment of capture from the pot to live well; however, the Clifton Channel site was equipped with two pots (~7 m long × 4.3 m wide × 6 m deep; 6.35 cm stretch knotless mesh) located at both upstream and downstream ends of the heart (Fig. 2b). Abandoning brailing methods altogether, the upstream and downstream pots were designed specifically to passively ramp and funnel fishes against ebb and flood tides, respectively, to attached live wells positioned centrally at the apex of each pot compartment (Fig. 2b). Depending on the tide, operators would deploy the upstream or downstream pot toward the riverbed to allow for capture of fishes migrating against the tidal current from the heart. Once within the pot compartment, free-swimming fishes were guided volitionally against the current toward the apex of the pot to the live well.

Mirroring Tuohy et al. (2020), each live well was aluminum framed with 3.81-cm knotless-nylon mesh walls to enable fresh river water to constantly flow through the trough. The live well was equipped with two parallel rectangular chambers (2.74 × 0.61 × 0.76 m) and a mesh pivot capture door near the entrance of the live well from the pot. Operators could open or close the capture door of the live well to passively entrap migrating fishes in one chamber while enabling the adjacent chamber to occupy. Within the shallow live well, the free-swimming catch could be identified to species and adipose fin-clip status (indicating hatchery and wild origins) with underwater video cameras (Splashcam Deep Blue) or by observation from above the water surface. In a commercial setting, hatchery fishes identified by a clipped adipose-fin could be dip-netted from the live well for selective harvest; wild-origin salmonids and bycatch species could be passively released though a submerged exit door without handling or air exposure (Fig. 3). However, for this study it was necessary for operators to wade within the live well to restrain the catch for data collection purposes.

2.2.1. Chinook salmon survival study design

Research for spring-run and summer-run Chinook salmon was conducted in the lower Columbia River between May 5 and July 2, 2019 to fill existing data gaps for these Chinook salmon runs and provide an estimate of adult salmonid post-release survival for passively operated fish traps. Mark-recapture studies for estimation of Chinook salmon survival had been encouraged by resource managers; therefore, a tagging methodology was pursued for the species.

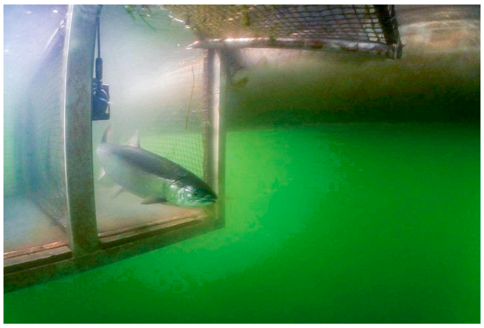


Fig. 3. Wild-origin coho salmon and other bycatch species could be passively captured with the modified fish trap, identified with underwater video cameras, and released though a submerged exit door without entanglement, brailing, human handling, or air exposure. Photo by Conrad Gowell. [Intended for color reproduction].

Similar to concurrent studies of sockeye salmon post-release survival (Tuohy et al., 2020), trap operators began a fishing event by deploying the pot compartment from its suspended position above the water column toward the river bottom. Pot tunnels were then opened, enabling the capture of free-swimming fish from the pot compartment for data collection. In capturing the catch for this mark-recapture tagging experiment, fishes were either (1) exposed to brailing en masse via the bunt of the pot net, or (2) passively captured and unexposed to brailing. It must be noted that greater effort was made to sample via passive capture operations (rather than brailing) to provide a more robust survival estimate for the newly developed fishing technique. During all operations, 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 (exposed to brailing or unexposed to brailing). Tunnel doors remained open to fish passage until a pause or cessation of fishing was desired.

When a fish was captured through any means, the catch was restrained by hand or rubberized dip-net for data collection. Although commercial fisheries using the passive operation with the gear-type are designed to eliminate fish handling and air exposure, restraining the catch by hand or dip-net remained necessary for conducting the survival study. Wading within the live well, biologists or fishers enumerated, measured (fork-length (FL)), and identified all specimens by species and adipose fin-clip status. All salmonids (regardless of their adipose fin-clip status) 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. All Chinook salmon lacking an existing PIT-tag (100 % of those encountered) and > 400 mm FL were tagged in the peritoneal cavity with a 12.5-mm, 134.2- kHz, full-duplex PIT-tag using a MK-25 Rapid Implant Gun (Biomark). These fish were then scanned to record PIT-tag information and a 1 mm caudal fin clip tissue sample was secured for future genetic processing by the Columbia River Inter-Tribal Fish Commission (CRITFC) Hagerman Genetics Laboratory. With all data collected, each fish was passively released through the live-well exit door for upriver detection at Bonneville Dam (rkm 234). Any fish that showed no signs of life at capture or release was noted as an immediate mortality.

2.2.2. Chinook salmon survival analysis

To determine where each PIT-tagged Chinook salmon was likely to migrate post-release from the fish trap, genetic samples were processed by CRITFC (Hess et al., 2021). Using a combination of Genetic Stock Identification (GSI) and Parentage Based Tagging (PBT) methods, Hess et al. (2021) assigned each PIT-tagged Chinook salmon to one of 19 established Columbia River Basin population reporting groups. With genetic assignment results paired with each PIT-tagged Chinook salmon, the sample was filtered for individuals genetically assigned to upper-basin population reporting groups originating above Bonneville Dam PIT-tag arrays (rkm 234). For the sample collected in this study, upper-basin reporting groups consisted of the Klickitat River spring-run (KLICKR), the Hells Canyon spring-run (HELLSC), the South Fork Salmon River spring-run (SFSALM), the upper Salmon River spring-run (UPSALM), and the upper Columbia River summer-/fall-run (UCOLSF). Lower-basin reporting groups consisted of the Columbia Rogue (YOUNGS), the West Cascade spring-run (WCASSP), and the Willamette River spring-run (WILLAM) (Hess et al., 2021). All PIT-tagged Chinook salmon genetically assigned to these lower-basin reporting groups were removed from the analysis given their tendency to remain below Bonneville Dam PIT-tag arrays. In regard to the accuracy of genetic assignment methods in identifying spring-run and summer-run Chinook salmon originating from these defined upper-basin population groups in the Columbia River, it must be noted that the confidence of assignment to the pooled upper-basin reporting group was nearly 100 % (Hess et al., 2021).

Given the PIT-tagged Chinook salmon sample that had genetically assigned to upper-basin reporting groups, we used an unpaired single release–recapture method to estimate the joint probability of survival and detection for Chinook salmon released from each treatment group between the fish trap site (rkm 67) and Bonneville Dam (rkm 234). Bonneville Dam was selected as the final detection point primarily due to the fact that significant tribal gill net fisheries occurred upriver in the zone 6 fishery between Bonneville Dam and McNary Dam (with potential to bias unpaired survival estimates low above Bonneville Dam). Secondly, PIT-tag arrays at Bonneville Dam are known to have detection efficiencies for PIT-tagged adult salmon nearing 100 % (WDFW, 2014). Lastly, Vander Haegen et al. (2004) and Ashbrook (2008) had evaluated post-release survival of spring Chinook salmon from gill nets and tangle nets using Bonneville Dam as a final detection point. However, it is worth noting that our analysis of survival to Bonneville Dam occurred over a greater migration distance with the fish trap capture and tagging location located ~146 km downriver. In further contrast with relative survival studies of Vander Haegen et al. (2004) and Ashbrook (2008), our analysis was unpaired and lacked the ability to control for confounding factors such as tag loss, upriver predation, sport fisheries, and handling/tagging mortality effects. This was due to the fact that an insufficient sample of adult Chinook salmon ($n = 4$) that had been previously tagged in the juvenile life-stage was redetected at PIT-tag arrays in the lower river during the May 5 - July 2 study period to function as a viable control group. Furthermore, no other control sourcing method for capture and tagging of fishes in the adult life-stage appeared lower-impact than passive operations with the commercial fish trap within the study region. Therefore, the unpaired analysis of post-release survival in this study was inherently conservative, with the survival estimate prone to negative bias.

Upriver detection histories for PIT-tagged spring-run and summer-run Chinook salmon in 2019 were downloaded on November 19, 2019, from the Columbia Basin PIT-Tag Information System (PTAGIS), which provides public access to all PIT-tag detection data throughout the Columbia River Basin. It must be noted that one additional PIT-tagged Chinook salmon (Code: 3DD.003C06B8DA; passive treatment, tagged on June 16) that failed to upload to the PTAGIS database was detected at Bonneville Dam on June 24. Given interrogations of the tagged sample 167 km upstream at Bonneville Dam, the observed detection rate was directly estimated by a binomial proportion (p = # detected/# total tagged) with associated binomial variance. Observed detection was used as a proxy for post-release survival assuming Bonneville Dam PIT-tag arrays had detection efficiencies of 100 %. Similar to other Columbia River alternative fishing gear survival studies (WDFW, 2014; Tuohy et al., 2019), cumulative survival (representing the total estimated mortality effect from fish trap capture and release processes) was calculated for pooled hatchery and wild-origin Chinook salmon as the product of immediate survival at release from the gear (S_0 = # survived/# encountered) and post-release survival to Bonneville Dam (S_1). The 95 % profile likelihood confidence interval was estimated through Program USER (Skalski and Millspaugh, 2006; http://www.cbr.washington.edu/analy sis/apps/user). In the case of no observed mortality, a lower one-tailed interval estimate of survival was calculated using the method in Skalski (1981).

2.2.3. Coho salmon survival study design

The net pen holding studies conducted in 2020–2021 were similar in design to those conducted by Buchanan et al. (2002), Takata and Johnson (2018), and Tuohy et al. (2020) in which coho salmon were captured with a commercial gear and released into captivity to directly observe mortalities over a set period of time. This methodology of estimating post-release survival was selected for four primary reasons: (1) coho salmon mostly spawn in tributaries of the lower Columbia River below mainstem dam PIT-tag arrays; (2) technologies to detect PIT-tags or radio tags below Bonneville Dam are insufficient to meet model assumptions for release-recapture (WDFW, 2014); (3) previous alternative gear studies specific to coho salmon in the lower Columbia River have mostly relied upon a net pen holding methodology to estimate post-release survival (Takata and Johnson, 2018); and (4) resource managers had encouraged use of the net pen holding methodology for coho salmon, specifically.

Mirroring Takata and Johnson (2018) in the timeframe of study in the lower Columbia River, net pen holding studies were conducted from late September through October 2020 when commercial coho salmon fisheries commonly occur. Our studies observed coho salmon survival from the passive trapping process over 2 d and 4 d post-release periods in water temperatures ranging from 16.7 °C to 19.3 °C—conditions warmer than that of Takata and Johnson (2018) for evaluation of tangle nets. At the recommendation of management agency representatives, the study period in 2021 was shifted earlier than any prior coho salmon net pen holding study conducted in the lower Columbia River to evaluate 6 d post-release survival of the species in adverse water quality conditions in early September. It must be noted that study investigators anticipated confounding mortality effects from prolonged confinement in nearly lethal water quality conditions exceeding 20 °C (EPA, 2003, 2021; Donaldson et al., 2011).

On research days in each year of study, trap operators deployed the pot of the gear to the river bottom and opened the tunnel doors to initiate the soak period. Observers noted the set time, water temperature (°C; Extech), and presence of marine mammals. With the soak period initiated, the pot and live well of the modified fish trap was monitored to determine fish entrance and occupancy. Once a live well chamber was occupied by one or more fishes, operators passively trapped the catch through closure of the capture door. Captured fishes were enumerated, measured (FL), noted for capture/release conditions (“lively,” “lethargic,” or “no signs of life”; Takata and Johnson, 2018), and identified by species and adipose fin-clip status. After all data were collected, salmonids were released to resume the upriver migration unless criteria were met for inclusion in coho salmon net pen holding studies.

During collection of net pen holding samples, adult coho salmon (> 47 cm FL) captured with the modified trap were restrained by hand and transferred individually with a rubberized dip net to a designated temporary holding chamber of the live well until a sample of approximately 29–44 fish was retained. With the desired sample size achieved after a 4–12 h collection period, investigators sealed outlets to all pot tunnels. Coho salmon were once again restrained by hand, enumerated, identified by origin (adipose fin clipped or unclipped), measured (FL), noted for capture condition, and transferred from the live well by hand or dip-net to the sealed pot compartment (now functioning as a net pen holding chamber with dimensions similar to Takata and Johnson, 2018). Once the last fish was released into the net pen, investigators initiated holding periods of 0–2 d (S_1), 2–4 d (S_2), and 4–6 d (S_3). With the holding study underway, a biologist was stationed on site to note the date, time, water temperature (°C; Extech), and presence of marine mammals. As in previous studies (Takata and Johnson, 2018), coho salmon that exhibited significant predator-induced injuries or previous damage from gill nets were excluded from the holding study.

2.2.4. Coho salmon survival analysis

Post-release survival of pooled hatchery-origin and wild-origin coho salmon was estimated by holding and observing three trial groups (sample size mean = 35, min = 29, max = 38) for a 4-d period in 2020 and five trial groups (sample size mean = 40, min = 38, max = 44) for a 6-d period in 2021. To determine fish mortalities during the holding periods, samples were checked at least once daily at regular intervals from above and below the water surface (via snorkel/free-dive and underwater video survey). At the end of the holding period, all fish in the pen were enumerated, measured (FL), identified for species type and adipose fin-clip status, noted for condition (“lively,” “lethargic,” or “no signs of life"), and released to resume the upriver migration.

At the conclusion of each research season, data from the trial groups were pooled within each defined post-release period—0–2 d (S_1), 2–4 d (S_2), and 4–6 d (S_3). Post-release survival in each period was directly estimated by a binomial proportion ($p = \#$ survived/# total) with associated binomial variance. Cumulative survival ($S_0 * S_1 * S_2 * S_3$) was calculated as the product of immediate survival (S_0) and post-release survival ($S_1 * S_2 * S_3$) with the 95 % profile likelihood confidence interval estimated through Program USER (Skalski and Millspaugh, 2006). In the case of no observed mortality, a lower one-tailed interval estimate of survival was calculated using the method in Skalski (1981). For these post-release survival studies, it must be noted that potentially confounding mortality effects from factors such as net pen confinement, environmental stressors, natural mortality, and research processes (e.g., fish handling and dip-netting on two occasions to restrain fish during data collection and transfer to the holding pens) were not controlled.

3. Results

3.1. *Chinook salmon*

Between May 5 and July 2, 2019, at the Cathlamet, WA fish trap site, a total of 146 spring and summer-run Chinook salmon (71.2 % adipose fin-clipped) were genetic sampled and PIT-tagged for a mark-recapture analysis. In efforts to restrain the catch in the live well for genetic sampling and tagging, 114 were captured through passive operations with the fish trap and 32 fish were captured via brailing with the bunt of the pot net. Of the total tagged and genetic sampled population, 80 were classified by capture date as spring-run (< 15 June) and 66 were summer-run (> 15 June). During all gear operations, tagging, and genetic sampling, zero Chinook salmon adult or jack immediate mortalities occurred, resulting in an immediate survival estimate of $\widehat{S}_0 = 1.000$ (95 % CI: $S \geq 0.982$) for returning adults and jacks. Water temperatures ranged from 13.4 °C to 19.2 °C (mean = 16.3 °C). On three separate occasions, a California Sea Lion (*Zalophus californianus*) was observed within the vicinity of the trap site for periods less than ~10 min; no fish predation was observed by the study investigators during these incidents.

Stock composition of the sampled Chinook salmon population was estimated through a combination of GSI and PBT by Hess et al. (2021), resulting in genetic stock assignments for 142 PIT-tagged Chinook salmon to defined Columbia River Basin population reporting groups (Table 1). For the PIT-tagged Chinook salmon that were captured through passive operations with the fish trap and paired with genetic assignment data ($n = 110$), 88 fish (80.0 %) were assigned to upper-basin reporting groups above Bonneville Dam (i.e., SFSALM, UPSALM, and UCOLSF) and 22 fish (20.0 %) were assigned to lower-basin reporting groups below Bonneville Dam (i.e., WCASSP and WILLAM) (Table 1). Of the PIT-tagged Chinook salmon captured via brailing operations and paired with genetic assignment data ($n = 32$), 19 fish (59.4 %) were assigned to upper-basin reporting groups above Bonneville Dam (i.e., UCOLSF, HELLSC, and KLICKR) and 13 fish (40.6 %) were assigned to lower-basin reporting groups below Bonneville Dam (i.e., YOUNGS, WCASSP, and WILLAM) (Table 1).

Table 1
Spring-run and summer-run Chinook salmon were genetically assigned to Columbia River Basin population reporting groups above and below the PIT-tag array at Bonneville Dam by Hess et al. (2021). Upper-basin reporting groups consisted of the Klickitat River spring-run (KLICKR), the Hells Canyon spring-run (HELLSC), the South Fork Salmon River spring-run (SFSALM), the upper Salmon River spring-run (UPSALM), and the upper Columbia River summer-/fall-run (UCOLSF). Lower-basin reporting groups consisted of the Columbia Rogue (YOUNGS), the West Cascade spring-run (WCASSP), and the Willamette River spring-run (WILLAM).

Upper or lower-basin genetic assignment	Genetic reporting group	Passive treatment	Brailed treatment
Lower-basin (below Bonneville Dam)	YOUNGS	0	1
	WCASSP	2	1
	WILLAM	20	11
Total tagged and assigned below Bonneville Dam:		**22**	**13**
Upper-basin (above Bonneville Dam)	KLICKR	0	1
	HELLSC	0	2
	SFSALM	1	0
	UPSALM	1	0
	UCOLSF	86	16
Total tagged and assigned above Bonneville Dam:		**88**	**19**

Given the Chinook salmon samples that were PIT-tagged and successfully paired with upper Columbia River Basin genetic assignment data for passive operations ($n_{\text{passive}} = 88$) and brailing operations ($n_{\text{brailing}} = 19$), detection rates for each group were determined at PIT-tag arrays at or above Bonneville Dam (Table 2). For upper-basin Chinook salmon exposed to passive operations with the fish trap, observed detection was 1.000 (95 % CI: $S \geq 0.970$). For upper-basin Chinook salmon exposed to brailing operations, observed detection was 0.947 (95 % CI: $0.788 \leq S \leq 0.997$) (Table 2). The one fish that was not detected at Bonneville Dam from the brailed sample (assigned to UCOLSF) did not appear to have evaded detection based upon data from arrays positioned upriver of Bonneville Dam. Given the observed detection results, detection differed between passive and brailed samples at the $\alpha = 0.05$ level ($|Z| \geq 2.162$, $P = 0.03$). For the two treatment groups, mean migration time over the total 167 km distance from the fish trap to Bonneville Dam was estimated at 6.5 d (95 % CI: $5.7 \leq M \leq 7.3$) for the passively captured treatment group and 7.3 d (95 % CI: $5.6 \leq M \leq 9.0$) for the brailed treatment group.

3.2. *Coho salmon*

Between September 25 and October 15, 2020, a 4-d net pen holding study was conducted at the Cathlamet, WA fish trap site for coho salmon captured using passive operations. During the research period, water temperatures ranged from 16.7ºC to 19.3ºC (mean = 18.1ºC). Encountering 2209 adult coho salmon in the fall 2020 fishing season, there were zero adult immediate mortalities resulting in an immediate survival estimate of $\widehat{S}_0 = 1.000$ (95 % CI: $S \geq 0.999$). A total of 105 coho salmon (71.4 % adipose fin-clipped) were held in captivity post-release from the commercial gear in three separate trial groups (Table 3). No mortalities occurred within 0–2 d, nor did any mortalities occur between 2 and 4 d for post-release survival estimates of $\widehat{S}_1 = 1.000$ (95 % CI: $S_1 \geq 0.975$) and $\widehat{S}_2 = 1.000$ (95 % CI: $S_2 \geq 0.975$), respectively (Table 4). All coho salmon encountered during the fish collection process for the 2020 holding study were lively and vigorous upon capture and release after 4 d, with zero fish appearing lethargic. However, the snout and caudal fins of all fish appeared moderately abraded upon release after 4 d of confinement in the net pen environment.

In 2021, a 6-d net pen holding study was conducted at the Clifton, OR fish trap site for coho salmon captured using passive operations. This

Table 2
The spring-run and summer-run Chinook salmon sample size, PIT-tag detections, observed detection rate at Bonneville Dam, and the associated 95 % profile likelihood confidence interval (in parentheses) are shown for passively captured and brailed treatment groups.

Category	**Passive treatment**	**Brailed treatment**
Detected at Bonneville Dam	88	18
Total tagged and assigned to populations above Bonneville Dam	88	19
Observed detection rate	**1.000 (0.970 – 1.000)**	**0.947 (0.788 – 0.997)**

Table 3
Coho salmon mortalities were observed over 0–2 d, 2–4 d, and 4–6 d net pen holding periods in the fall of 2020–2021. The observation date, sample size, fish mortalities, and mean water temperature are shown for each trial group.

Year	Trial group	Dates	Mean water temperature (°C) and 95 % confidence interval	0–2 d		2–4 d		4–6 d	
				n	Mortalities	*n*	Mortalities	*n*	Mortalities
2020	1	25 Sep–29 Sep	18.6 (18.5–18.7)	38	0	38	0	–	–
	2	4 Oct– 8 Oct	18.4 (18.3–18.5)	38	0	38	0	–	–
	3	11 Oct– 15 Oct	17.2 (17.1–17.3)	29	0	29	0	–	–
	Total	25 Sep– 15 Oct	18.1 (17.9–18.2)	105	0	105	0	–	–
2021	1	3 Sep– 9 Sep	20.4 (20.2–20.5)	38	1	37	0	37	0
	2	9 Sep– 15 Sep	20.3 (20.2–20.5)	39	0	39	1	36	3
	3	16 Sep– 22 Sep	19.3 (19.1–19.4)	38	0	38	0	38	1
	4	23 Sep– 29 Sep	18.7 (18.5–18.8)	44	0	44	0	44	1
	5	29 Sep– 5 Oct	17.9 (17.8–18.1)	41	0	41	0	41	0
	Total	3 Sep– 5 Oct	19.3 (19.1–19.5)	200	1	199	1	196	5

Table 4
Immediate and post-release survival of coho salmon was estimated in 2020 and 2021. Associated 95 % confidence intervals are provided in parentheses.

Year	Survival estimate and 95 % confidence interval				
	Immediate	(>0–2 d)	(2–4 d)	(4–6 d)	Cumulative
2020	1.000 (0.999–1.000)	1.000 (0.975–1.000)	1.000 (0.975–1.000)	–	1.000 (0.975–1.000)
2021	0.999 (0.997–0.9998)	0.995 (0.978–0.9997)	0.995 (0.978–0.9997)	0.974 (0.946–0.991)	0.964 (0.947–0.968)

study was conducted earlier in the fall fishing season than prior years, with fish collection dates occurring as early as a sufficient sample of coho salmon could be collected between September 3 and September 29. Throughout the net pen holding experiment, water temperatures ranged from 17.4ºC to 20.9ºC (mean = 19.3ºC). Encountering 1790 adult coho salmon over the 2021 fishing season, two adult immediate mortalities occurred due to predator-induced injury. Based upon the freshness of the wounds, investigators assumed these injuries occurred in the vicinity of the trap site, resulting in an immediate survival estimate of $\widehat{S}_0 = 0.999$ (95 % CI: $0.997 \leq \widehat{S}_0 \leq 0.9998$).

A total of 200 coho salmon (90.5 % adipose fin-clipped) were held in captivity post-release from the commercial gear for a 0–2 d duration in five separate trial groups (Table 3). One mortality occurred during the 0–2 d holding period for a post-release survival estimate of $\widehat{S}_1 = 0.995$ (95 % CI: $0.978 \leq \widehat{S}_1 \leq 0.9997$) (Table 4).

With one mortality occurring during the 0–2 d holding period, a total of 199 coho salmon were held in captivity for the 2–4 d holding period in five separate trial groups (Table 3). Similar to the 0–2 d holding period, one mortality occurred between 2 and 4 d of confinement for a survival estimate of $\widehat{S}_2 = 0.995$ (95 % CI: $0.978 \leq \widehat{S}_2 \leq 0.9997$) (Table 4).

Given the two total mortalities that occurred within the 0–2 d and 2–4 d holding periods and removing two fish from the sample due to pinniped predation within the holding pen, a total of 196 coho salmon were held in captivity for the 4–6 d holding period in five separate trial groups (Table 3). Between 4 and 6 d of confinement, five mortalities occurred (Table 3). From these results, 4–6 d survival was estimated at $\widehat{S}_3 = 0.974$ (95 % CI: $0.946 \leq \widehat{S}_3 \leq 0.991$). From these findings, we estimated total post-release survival (i.e., $S_1 * S_2 * S_3$) in 2021 to be 0.965 (95 % CI: $0.948 \leq post - \widehat{release} \leq 0.969$). Incorporating immediate survival, cumulative survival was estimated at 0.964 (95 % CI: $0.947 \leq \widehat{cumulative} \leq 0.968$) (Table 4).

Similar to prior years of study, all coho salmon encountered during the fish collection process for the holding study were lively and vigorous upon capture with no signs of physical injury related to the commercial gear. Those that survived the 6 d holding period to release also appeared lively and vigorous despite considerable abrasion to the snout and caudal fins from prolonged confinement in the net pen environment. Cause of death for the mortalities within this study could not be determined from autopsy but likely were the result of the pooled effect of natural mortality, confinement in the net pen environment during adverse water temperature conditions (> 20 °C), and potential stressors from passive capture and research processes.

4. Discussion

Research findings over these three years of study at two separate fish trap sites further suggest that recently developed commercial fish trapping techniques can allow for selective harvesting of hatchery produced fish (and other abundant fish runs) while achieving nearly 100 % post-release survival of ESA-listed adult salmonids. Using mark-recapture and net pen holding techniques to estimate post-release survival of coho salmon and Chinook salmon (both spring-run and summer-run stocks), results for each species and methodology mostly validate the findings of prior survival studies for sockeye salmon, coho salmon, fall-run Chinook salmon, and summer-run steelhead from passive operations with the gear (Tuohy et al., 2020; Cox and Sippel, 2020) (Table 5). Evaluating detections of PIT-tagged spring-run and summer-run Chinook salmon that were genetically assigned to population reporting groups above Bonneville Dam (Hess et al., 2021), observed detection of the passively captured and released treatment group at Bonneville Dam was 1.000 (95 % CI: $S \geq 0.970$) over a 6.5 d, 167 km migration. Given

Table 5

Stock-specific post-release survival estimates and 95 % confidence intervals are shown for all studies relevant to passive operations with fish traps between 2017 and 2021 (Cox and Sippel, 2020[a]; Tuohy et al., 2020[b]).

Salmonid stock	Study period	Water temperature (°C)	Study methodology	Survival estimate and 95 % confidence interval
Summer steelhead	Aug-Sep, 2017	18.7 – 22.3	Paired mark-recapture[a]	1.000 (0.783 – 1.000)
Fall Chinook	Aug-Sep, 2017	18.7 – 22.3	Paired mark-recapture[a]	1.000 (0.752 – 1.000)
Spring/Summer Chinook	May-Jul, 2019	13.4 – 19.2	Unpaired mark-recapture	1.000 (0.970 – 1.000)
Sockeye	May-Jul, 2019	14.4 – 19.2	Paired mark-recapture[b]	1.000 (0.974 – 1.000)
Coho	Sep-Oct, 2019	12.1 – 19.2	Unpaired net pen holding (2 d)[b]	1.000 (0.978 – 1.000)
Coho	Sep-Oct, 2020	16.7 – 19.3	Unpaired net pen holding (4 d)	1.000 (0.975 – 1.000)
Coho	Sep-Oct, 2021	17.4 – 20.9	Unpaired net pen holding (6 d)	$>$ 0.965 (0.947 – 0.968)

that this unpaired analysis lacked a control group to adjust for confounding factors such as tag loss and mortality effects from research handling and tagging, upriver predation, fisheries, and the natural environmental baseline, the study methodology for survival estimation was inherently conservative and prone to negative bias. Therefore, the survival estimate of 1.000 from this study of spring-run and summer-run Chinook salmon supports the conclusion that actual survival was at or near 1.000. Although there may seem to be sample size limitations, the fact that 88 of 88 of the PIT-tagged sample that had assigned to upper-basin populations were detected at Bonneville Dam in the absence of a control group (Table 2) is highly persuasive and corroborates the findings of prior studies for passively operated fish traps that estimated survival at 1.000 (Table 5; Tuohy et al., 2020; Cox and Sippel, 2020).

Mark-recapture post-release survival findings for the passively operated fish trap are further supported by the net pen holding results for coho salmon in 2020–2021. Similar to Tuohy et al. (2020) that estimated coho salmon post-release survival from passive operations with fish traps at $\widehat{S}_1 = 1.000$ (95 % CI: $S_1 \geq 0.978$) over 0–2 d in 2019, we estimated 0–2 d post-release survival at $\widehat{S}_1 = 1.000$ (95 % CI: $S_1 \geq 0.975$) in 2020 and $\widehat{S}_1 = 0.995$ (95 % CI: $0.978 \leq \widehat{S}_1 \leq 0.9997$) in 2021. Similarly, over 4 d of confinement, we estimated post-release survival at $\widehat{S}_2 = 1.000$ (95 % CI: $S_2 \geq 0.975$) in 2020 and $\widehat{S}_2 = 0.995$ (95 % CI: $0.978 \leq \widehat{S}_2 \leq 0.9997$) in 2021. These survival results for coho salmon are equivalent to the mark-recapture results for spring-run and summer-run Chinook salmon from 2019.

Although findings for 4–6 d net pen holding deviate from the conclusions of all other studies for passively operated fish traps with post-release survival estimated at $\widehat{S}_3 = 0.974$ (95 % CI: $0.946 \leq \widehat{S}_3 \leq 0.991$), it must be noted that the net pen holding methodology lacked a control group to adjust for confounding mortality factors including confinement in nearly lethal water quality conditions, the natural environmental baseline, and research processes (e.g., dip-netting, fish handling, and other stressors unique to the study and absent from commercial processes). Based upon the environmental conditions experienced during the 2021 holding study, it is likely that the few mortalities that occurred between 4 and 6 d of captivity were primarily due to the prolonged effects of confinement in sublethal to lethal water quality conditions and abrasion in the holding pen. During the holding period for trial group two when the majority of the long-term mortalities occurred (Table 3), water temperatures consistently neared or exceeded thresholds identified as potentially lethal for fall runs of salmon in the Columbia River (20–22 °C; Coutant, 1970; Becker, 1973; EPA, 2003; EPA, 2021), with the mean temperature during captivity estimated at 20.3 °C (95 % CI: 20.2 °C $\leq \widehat{temp} \leq$ 20.5 °C). In the captive net pen environment, fishes in the study could not find temperature refugia available in the wild and remained subject to adverse water quality conditions ($>$ 20 °C) known to increase fish susceptibility to disease, parasites, stress, and mortality (Fryer and Pilcher, 1974; Groberg et al., 1978; Richter and Kolmes, 2005).

In addition to the likely mortality effects from adverse water quality conditions, the mortality effects of prolonged net pen confinement on wild fish survival are well-established in the scientific literature (Portz et al., 2006; Donaldson et al., 2011; Raby et al., 2015a, 2015b). Donaldson et al. (2011) demonstrated that sockeye salmon held in confinement for 1 d resulted in substantial physiological stress and significantly higher mortality than fish unexposed to net pen confinement. Raby et al., 2015a, 2015b drew similar conclusions for coho salmon, determining that physiological stress and the time-specific rate of mortality was higher for fish held in net pens for 1 d than fish tagged and immediately released. Based upon the evidence, it is clear that wild adult salmon experience severe physiological stress from prolonged periods of net pen confinement that can increase the likelihood of mortality from various factors, including lethal water quality conditions. This may be the reason that virtually all holding studies used to set official gear mortality rates have been conducted over 1–3 d holding periods (Raby et al., 2015a, 2015b). Considering that few known post-release mortality studies for coho salmon have been conducted over a period of 6 d or longer (Takata and Johnson, 2018) and no known commercial fishery mortality study to date has ever held salmon in net pens where water temperatures commonly exceeded 20 °C, it is likely that coho salmon post-release survival results from 2021 were biased low and the true survival effect from passive operations with the fish trap exceeded that of 0.974 during the 4–6 d holding period.

While these post-release survival studies generally validate the findings of previous studies conducted for passively operated fish traps (Table 5), Chinook salmon survival results also corroborate the findings of Tuohy et al. (2020) and Cox and Sippel (2020) in supporting the hypothesis that bycatch survival from passively operated fish traps exceeds that of prototype brailing operations. Although the sample size for the brailed treatment group was limited ($n = 19$) and results for the treatment should be viewed with caution, the observed detection rate of 0.947 (95 % CI: $0.788 \leq S \leq 0.997$) at Bonneville Dam was similar to Cox and Sippel's (2020) survival estimate of $S = 0.935$ (95 % CI: $S \geq 0.648$) for upper-basin fall-run Chinook salmon released from brailing operations. For passive operations with the fish trap, our analysis of PIT-tagged spring-run and summer-run Chinook salmon demonstrated that the joint probability of survival and detection over 167 km to Bonneville Dam was 1.000 (95 % CI: $S \geq 0.970$), exceeding that of brailing operations ($|Z| \geq 2.162$, $P = 0.03$). Once again, this conclusion mirrors that of Cox and Sippel (2020) that compared brailing vs. passive operations and similarly estimated survival of upriver-basin fall-run Chinook salmon from passive operations with fish traps at 1.000 (95 % CI: $S \geq 0.752$) = 0.95). The same significant difference in survival was found by Tuohy et al. (2020) in an analysis of brailing vs. passive operations for sockeye salmon. By addressing the primary physical and physiologically factors known to impact bycatch survival (Donaldson et al., 2014; Raby et al., 2015a, 2015b), it appears that use of passive operations with fish traps provides survival benefits to encountered salmonid bycatch stocks. Nevertheless, statistical differences in survival between treatment groups from this study must be viewed with caution given the small sample size collected for the brailed treatment group.

4.1. Conclusions

The primary strength of this research is the simplicity of the methods and the strikingly high bycatch survival results achieved for all methods of fish trap operation despite the inherent negative biases within the statistical analyses. Various studies relevant to passively operated fish traps have now been conducted demonstrating bycatch survival at or near 1.000 (Tuohy et al., 2020; Cox and Sippel, 2020; Table 5); however, there is perhaps no evidence as simple and persuasive as that from these three unpaired mark-recapture and net pen holding studies conducted at two separate fish trap sites across three seasons in the lower Columbia River. With the inability to control for well-known confounding mortality factors, post-release survival was 1.000 for spring-run and summer-run Chinook salmon in 2019; for coho salmon, post-release survival was estimated at 1.000 and 0.965 in 2020 and 2021, respectively. Given these estimates of post-release survival and the collective evidence from other prior studies of passively operated fish traps (Table 5), it is evident that the fishing practice may allow for selective harvesting of targeted fish stocks while minimizing bycatch mortality of ESA-listed adult salmonids in Pacific Northwest fisheries. Furthermore, the results demonstrate that passively operated fish traps may provide increased opportunities for low-impact salmonid population monitoring and serve as a zero-mortality control group to fill data gaps for other poorly understood commercial or recreational fishing gears used within the Columbia River and elsewhere throughout the region. Ultimately, findings of these studies may be applied to improve management of Pacific Northwest salmon fisheries, inform the implementation of alternative gear fisheries, and protect the diversity and abundance of ESA-listed wild salmonids for recovery.

CRediT authorship contribution statement

Adrian M. Tuohy: Conceptualization, Methodology, Funding Acquisition, Resources, Project Administration, Investigation, Data Curation, Formal analysis, Writing – original draft, Writing – review & editing, Visualization. **Aaron T. Jorgenson:** Conceptualization, Methodology, Project Administration, Investigation, Data Curation, Validation, Writing – review & editing, Visualization. **John R. Skalski:** Supervision, Software, Validation, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

All data may be downloaded through the Wild Fish Conservancy webpage (https://wildfishconservancy.org/the-fish-trap-project/fish-trap-research/) by scrolling downward and clicking on the “Data” tab. All PIT-tag information can be accessed through the PTAGIS webpage (www.ptagis.com) using the code “CPN” and name “Cathlamet Pound Net.

Acknowledgements

This project was made possible by funding received under award NA17NMF4720255 and NA19NMF4720230 from the National Oceanic and Atmospheric Administration (NOAA) Fisheries Service, in cooperation with the Bycatch Reduction Engineering Program. Funding was also provided under award NA19NMF4270028 from NOAA Fisheries Service Saltonstall-Kennedy Grant Program. Additional support was provided from the Washington Department of Fish and Wildlife, Oregon Department of Fish and Wildlife, Patagonia, Inc., the Raynier Institute & Foundation, and the Burning Foundation. Beyond the funders of this work, the authors would like to thank the many people that collaborated and contributed to the study to make it a success: Kurt Beardslee, Jamie Glasgow, Joe Verrelli, Blake Joplin, Colleen McGee, Conrad Gowell, Danielle Dorsch, and Brennan Helwig of Wild Fish Conservancy; Dr. Jon E. Hess and the Columbia River Inter-Tribal Fish Commission Hagerman Genetics Laboratory; Lisa Harlan, Mark Sorel, Ryan Lothrop, and Bill Tweit of the Washington Department of Fish and Wildlife; commercial fishers Jon Blair Peterson and Billie Delaney; fish buyer and processor Mike Clark of C&H Fish Company; Seattle chef Renee Erickson of Sea Creatures; Shane Anderson of North Fork Studios; Craig Scanlan of Columbia Basin Research; and the University of Washington School of Aquatic and Fishery Sciences for faculty review.

References

Anderson, J., Warheit, K.I., Craig, B.E., Seamons, T.R., Haukenes, A.H., 2020. A review of hatchery reform science in Washington State. Final report to the Washington Fish and Wildlife Commission. Washington Department of Fish and Wildlife, Olympia, WA.

Ashbrook, C., 2008. Selective Fishing and Its Impacts on Salmon: A Tale Of Two Test Fisheries (Master’s thesis). University of Washington, Seattle, WA.

Becker, C.D., 1973. Columbia River thermal effects study: reactor effluent problems. J. Water Pollut. Control. Fed. 45 (5), 850–869.

Buchanan, S., Farrell, A.P., Fraser, J., Gallaugher, P., Joy, R., Routledge, R., 2002. Reducing gill-net mortality of incidentally caught coho salmon. N. Am. J. Fish. Manag 22, 1270–1275.

Cobb, J.N., 1930. Pacific Salmon fisheries. U.S. Bureau of Fisheries, Document 1092, Washington, D.C.

Coutant, C.C., 1970. Thermal resistance of adult Coho and jack Chinook salmon, and adult steelhead trout from the Columbia River. AEC Research and Development Report. Battelle Memorial Institute Pacific Northwest Laboratories, Richland, WA.

Cox, B., Sippel, T., 2020. Pound Net and PD7 2017 Survival Analysis: Recommended Release Mortality Rates for Pound Net Gear. Washington Department of Fish and Wildlife, Olympia, WA.

Cramer, S., Maule, A., Chapman, D., 1991. The Status of coho salmon in the Lower Columbia River. Report by Don Chapman Consultants, Inc., to Pacific Northwest Utilities Conference Committee, Portland, OR.

Davis, M.W., 2002. Key principles for understanding fish bycatch discard mortality. Can. J. Fish. Aquat. Sci. 59, 1834–1843.

Donaldson, M.R., Hinch, S.G., Patterson, D.A., Hills, J., Thomas, J.O., Cooke, S.J., Raby, G.D., Thompson, L.A., Robichaud, D., English, K.K., Farrell, A.P., 2011. The consequences of angling, beach seining, and confinement on the physiology, post-release behaviour and survival of adult sockeye salmon during upriver migration. Fish. Res. 108, 133–141.

Donaldson, M.R., Hinch, S.G., Jeffries, K.M., Patterson, D.A., Cooke, S.J., Farrell, A.P., Miller, K.M., 2014. Species and sex-specific responses of and recovery of wild, mature Pacific Salmon to an exhaustive exercise and air exposure stressor. Comp. Biochem. Physiol. 173, 7–16.

(Environmental Protection Agency) EPA, 2003. EPA Region 10 Guidance for Pacific Northwest State and Tribal Temperature Water Quality Standards. EPA 910-B-03-002. Region 10 Office of Water, Seattle, WA.

(Environmental Protection Agency) EPA, 2021. EPA Region 10 Columbia River Cold Water Refuges Plan. Region 10 Office of Water, Seattle WA.

Fryer, J.L., Pilcher, K.S., 1974. Effects of temperature on diseases of salmonid fishes. U.S. Environmental Protection Agency, Office of Research and Development. Ecological Research Series. EPA-660/3–73-020, Washington, D.C.

Gayeski, N.J., Stanford, J.A., Montgomery, D.R., Lichatowich, J., Peterman, R.M., Williams, R.N., 2018. The failure of wild salmon management: need for a place-based conceptual foundation. Fisheries 43, 303–309.

Groberg, W.J.Jr, McCoy, R.H., Pilcher, K.S., Fryer, J.L., 1978. Relation of water temperature to infections of coho salmon (*Oncorhynchus kisutch*), Chinook salmon (*Oncorhynchus tshawytsch*), and Steelhead Trout (*Salmo gairdneri*) with Aeromonas salmonicida and A. hydrophila. J. Fish. Res. Board Can. 35, 1–7.

Hatchery Scientific Review Group (HSRG), 2009. Columbia River hatchery reform system-wide report. HSRG, Seattle, WA. https://www.streamnet.org/home/data-maps/hatchery-reform/hsrg-reports.

Hess, J.H., Collins, E.E., Harmon, S.A., Horn, R.L., Koch, I., Stephenson, J., Willis, S., Narumet, S.R., 2021. Genetic Assessment of Columbia River Stocks. 1/1/2020 – 12/31/2020. Annual Report to the Bonneville Power Administration (BPA). 2008-907-00. Columbia River Inter-Tribal Fish Commission (CRITFC), Hagerman, ID.

Lichatowich, J., 1999. Salmon without Rivers. Island Press, Washington, D.C.

Lichatowich, J., Williams, R., Bakke, B., Myron, J., Bella, D., McMillan, B., Stanford, J., Montgomery, D., 2017. Wild Pacific salmon: a threatened legacy. Bemis Printing, St. Helens, OR. Available: ⟨http://www.salmonhistory.com/Pacific_salmon_legacy_after_printing_7_24_2017_new.pdf⟩.

Mahnken, C., Ruggerone, G., Waknitz, W., Flagg, T., 1998. A historical perspective on salmonid production from Pacific Rim hatcheries. North Pac. Anadromous Fish. Comm. Bull. 1, 38–53.

Naish, K.A., Taylor III, J.E., Levin, P., Quinn, T.P., Winton, J.R., Huppert, D., Hilborn, R., 2007. An evaluation of the effects of conservation and fishery enhancement hatcheries on wild populations of salmon. Adv. Mar. Biol. 53, 61–194.

(National Research Council) NRC, 1996. Upstream: Salmon and Society in the Pacific Northwest. National Academy Press, Washington, D.C.

National Marine Fisheries ServiceNMFS), 2018. Memo from NMFS to the U.S. v. Oregon Technical Advisory Committee: Release Mortality rates for fall season non-treaty commercial gillnet and tangle net gear. July 30, 2018.

(Northwest Fisheries Science Center) NWFSC, 2015. Status Review Update for Pacific Salmon and Steelhead Listed Under the Endangered Species Act: Pacific Northwest. National Oceanic and Atmospheric Administration, NWFSC, Seattle, WA.

(Oregon Department of Fish and Wildlife) ODFW, 2013. Oregon Administrative Rule 635-500-6705: guiding principles for Columbia River fisheries management. ODFW, Portland, OR.

Pacific States Marine Fisheries CommissionPSMFC). 2017. PTAGIS (PIT Tag Information System): advanced reporting. PSMFC, Portland, Oregon. Available: ⟨https://www.ptagis.org/data/advanced-reporting⟩ (Accessed November 2019).

Portz, D.E., Woodley, C.M., Cech Jr, J.J., 2006. Stress-associated impacts of short-term holding on fishes. Rev. Fish. Biol. Fish. 16, 125–170.

Raby, G.D., Hinch, S.G., Patterson, D.A., Hills, J.A., Thompson, L.A., Cooke, S.J., 2015a. Mechanisms to explain purse seine bycatch mortality of coho salmon. Ecol. Appl. 25 (7), 1757–1775.

Raby, G.D., Clark, T.D., Farrell, A.P., Patterson, D.A., Bett, N.N., Wilson, S.M., Willmore, W.G., Suski, C.D., Hinch, S.G., Cooke, S.J., 2015b. Facing the river gauntlet: understanding the effects of fisheries capture and water temperature on the physiology of coho salmon. PLoS One 10, e0124023.

Richter, A., Kolmes, S.A., 2005. Maximum temperature limits for Chinook, coho, and chum salmon, and steelhead trout in the Pacific Northwest. Rev. Fish. Sci. 13, 23–49.

Skalski, J.R., 1981. Statistical inconsistencies in the use of no-observed effect levels in toxicity testing. In: Branson, D.R., Dickson, K.L. (Eds.), Proceedings of the Fourth Annual Symposium on Aquatic Toxicology. American Society for Testing and Materials, Special Technical Publication 737, Philadelphia, PA, pp. 377–387.

State of Oregon, 1948. Oregon voters' pamphlet for the regular general election, November 2, 1948. Salem, OR.

Takata, H., Johnson, A., 2018. Post-release Mortality of Coho Salmon Captured with Tangle Nets in the Lower Columbia River. Oregon Department of Fish and Wildlife, Salem, OR.

Tuohy, A.M., 2018. Post-Release Survival of Chinook Salmon and Steelhead Trout from an Experimental Commercial Fish Trap in the Lower Columbia River (WA. Master's thesis). University of Washington, Seattle.

Tuohy, A.M., Skalski, J.R., Gayeski, N.J., 2019. Survival of salmonids from an experimental commercial fish trap. Fisheries 44, 423–432.

Tuohy, A.M., Skalski, J.R., Jorgenson, A.T., 2020. Modified commercial fish trap to help eliminate salmonid bycatch mortality. North Am. J. Fish. Manag. 40 (5), 1239–1251. https://doi.org/10.1002/nafm.10496.

US v. OR MA (U.S. v. Oregon Management Agreement), 2018. 2018–2027 U.S. v. Oregon Management Agreement. Available: ⟨https://critfc.org/documents/us-v-oregon-agreement⟩.

Utter, F., Epifanio, J., 2002. Marine aquaculture: genetic potentialities and pitfalls. Rev. Fish. Biol. Fish. 12, 59–77.

Vander Haegen, G., Ashbrook, C., Dixon, J., 2004. Survival of spring Chinook salmon captured and released in a selective commercial fishery using gill nets and tangle nets. Fish. Res. 68, 123–133.

Washington Department of Fish and WildlifeWDFW), 2018. Comprehensive evaluation of the Columbia River Basin salmon management policy C-3620, 2013–2017. Olympia, WA.

Washington Department of Fish and WildlifeWDFW), 2022. Salmon Conservation and Reporting Engine (SCoRE): population status - spawning. Olympia, WA. Available: ⟨https://fortress.wa.gov/dfw/score/score/species/species.jsp⟩ (Accessed April 2022).

Washington Fish and Wildlife CommissionWFWC), 2009. Washington Fish and Wildlife Commission hatchery and fishery reform policy decision. WFWC, Policy C-3619, Olympia, WA.

Washington Fish and Wildlife CommissionWFWC), 2013. Columbia River basin salmon management policy decision. WFWC, Policy C- 3620, Olympia, WA.

Washington Fish and Wildlife CommissionWFWC), 2015. Willapa Bay salmon management policy decision. WFWC, Policy C- 3622, Olympia, WA.

Washington State Session Laws, 1935. Twenty-fourth Session, Chapter 1: Fish Traps and Fishing Regulations. State Printing Plant, Olympia, WA.

(Washington Department of Fish and Wildlife) WDFW, 1997. Final Environmental Impact Statement for the Wild Salmonid Policy. WDFW, Olympia, WA.

(Washington Department of Fish and Wildlife) WDFW, 2014. Lower Columbia River Alternative Commercial Fishing Gear Mortality Study: 2011 and 2012. WDFW, Olympia, WA.

(Oregon Department of Fish and Wildlife (ODFW) and Washington Department of Fish and Wildlife) WDFW, 2020. Joint Staff Report: Stock Status and Fisheries for Fall Chinook Salmon, Coho Salmon, Chum Salmon, Summer Steelhead, and White Sturgeon. WDFW, Olympia, WA.

Glossary

CRITFC: Columbia River Inter-Tribal Fish Commission
ESA: Endangered Species Act.
GSI: Genetic stock identification methods for genetic assignment.
HELLSC: Hells Canyon spring-run.
KLICKR: Klickitat River spring-run.
PBT: Parentage based tagging methods for genetic assignment.
SFSALM: South Fork Salmon River spring-run.
TAC: U.S. v. Oregon Technical Advisory Committee.
UCOLSF: Upper Columbia River summer-/fall-run.
UPSALM: Upper Salmon River spring-run.
WCASSP: West Cascade spring-run.
WILLAM: Willamette River spring-run.
YOUNGS: Columbia Rogue.