State of Washington
DEPARTMENT OF FISH AND WILDLIFE
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December 30, 2022

The Honorable Christine Rolfes
Chair, Senate Ways and Means
303 John A. Cherberg Building
Post Office Box 40466
Olympia, WA 98504-0466

The Honorable Timm Ormsby
Chair, House Appropriations
315 John L. O'Brien Building
Post Office Box 40600
Olympia, WA 98504-0600

The Honorable Van De Wege
Chair, Senate Agriculture, Water
Natural Resources, and Parks
212 John A. Cherberg Building
Post Office Box 40424
Olympia, WA 98504-0424

The Honorable Mike Chapman
Chair, House Rural Development,
Agriculture, and Natural Resources
132B Legislative Building
Post Office Box 40600
Olympia, WA 98504-0600

Dear Chairs,

I am writing to provide you with the Washington Department of Fish and Wildlife's report to the legislature regarding the Cowlitz River salmon and steelhead hooking mortality study. Funding and the proviso language requires a report to the relevant committees of the legislature per language in our 2021-23 operating budget, which reads as follows:

> (35) $90,000 of the general fund—state appropriation for fiscal year 2022 is provided solely for the department to complete the final phase of the Cowlitz river salmon and steelhead hook mortality study. No less than $60,000 of the amount provided in this subsection is provided for the original contractor of the study to complete their work. A final report shall be provided to the appropriate committees of the legislature by December 31, 2022.

This proviso allowed WDFW and its contractor Mount Hood Environmental to complete analysis and report on a three-year field study completed on the Cowlitz River to evaluate the effects of recreational angling on the post-release survival of adult salmon and steelhead.

If you have any questions or concerns about this report, please feel free to contact Tom McBride, WDFW's Legislative Director, at (360)480-1472.

Sincerely,

Kelly Susewind
Director

Cowlitz Hooking Mortality Study

Washington Department of FISH and WILDLIFE

December, 2022

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Executive Summary

Proviso Background

The Washington State legislature identified a proviso in the 2021-2023 biennium operating budget for the Washington Department of Fish and Wildlife (WDFW) to complete a final report on the Cowlitz River Hooking Mortality study:

> “$90,000 of the general fund—state appropriation for fiscal year 2022 is provided solely for the department to complete the final phase of the Cowlitz river salmon and steelhead hook mortality study. No less than $60,000 of the amount provided in this subsection is provided for the original contractor of the study to complete their work. A final report shall be provided to the appropriate committees of the legislature by December 31, 2022.”

The intent of this proviso was to allow WDFW and its contractor Mount Hood Environmental (MHE) to complete analysis and reporting resulting from a three-year field study completed on the Cowlitz River to evaluate the effects of recreational angling on the post-release survival of adult salmon and steelhead. Prior to the 2021-2023 biennium, WDFW and MHE had been funded in 2017-2020, using Columbia River Salmon and Steelhead Endorsement (CRSSE) funds and subsequently some Fish Program funds to complete the field portion of the study. The goal of the final year proviso was to allow WDFW and MHE to finalize statistical analysis of data collected and prepare a scientific manuscript for publication in a peer-revied journal.

Project Budget

The project was funded for field data collection and interim annual reporting each year from 2017-2020. Final analysis and reporting were delayed in part due to the cessation of the intended funding source, the CRSSE. In 2021, the legislative proviso provided the necessary funding to complete the project.

Fiscal Years	Budget	Primary Tasks	Funding Source
2017-18	$180,581	Planning, Data Collection, Interim Reporting	CRSSE
2018-19	$172,499	Planning, Data Collection, Interim Reporting	CRSSE
2019-20	$198,923	Planning, Data Collection, Interim Reporting	CRSSE
2021-2	$90,000	Final Analysis and Report	Proviso
Total	$642,003		

Project Overview

Efforts to recover depressed stocks of salmon and steelhead in North America include implementation of mark-selective recreational fisheries by WDFW and other management agencies, whereby anglers are allowed to harvest hatchery-origin fish but must release natural-origin fish. Catch and release (C&R) is generally thought to be an effective tool for conservation due to high survival of released adult salmon and steelhead in freshwater. However, estimates of C&R mortality are necessary for conservation and management of populations to determine how many fish are killed post-release. Previous studies designed to estimate C&R mortality have produced highly variable results among species and size classes of fish, gear types, and environmental conditions. Moreover, many of these studies suffered from considerable variability in study design, sample sizes, and associated scientific rigor, making it challenging for WDFW and other managers to identify mortality rates for use in specific fisheries. Therefore, WDFW and other managers have often adopted C&R mortality rates based on qualitatively averaging the results of previous studies. In addition, WDFW and other managers often restrict use of certain angling methods and terminal tackle that are assumed to result in higher mortality, leading to diverse regulations developed with limited empirical basis.

Improved estimates of C&R mortality rates for adult salmon and steelhead would greatly benefit WDFW and other managers enabling development of management plans with stronger empirical support. To address this need, WDFW partnered with MHE to conduct a novel three-year mark-recapture study in the Cowlitz River, Washington to estimate effects of a variety of factors hypothesized to influence salmon and steelhead C&R survival using a treatment-control design. Three species of salmonids (including spring Chinook and coho salmon, and steelhead) were captured and released as treatments using various angling techniques and terminal tackle. Non-angled fish were captured in a trap and released back into the fishery to serve as controls. Statistical models were used to estimate the probability of recovery for both treatments and controls, where survival was estimated as the probability of recovery of treatments divided by controls.

Hooking mortality rates were generally very low and the effects of covariates on survival supported the results of previous research. Recovery rates of Coho salmon differed less than a percent between angled and non-angled fish across multiple gear types, indicating negligible effects of C&R. Angled Spring Chinook Salmon were predicted to experience 3.6% to 10.2% C&R mortality relative to non-angled control fish, depending on terminal tackle. Barbless hooks were associated with higher survival than barbed hooks for both Chinook and Coho Salmon, although differences were small for Chinook and negligible for Coho. In contrast, steelhead angled on barbed hooks were recovered at slightly higher rates than those caught on barbless hooks. We also found strong evidence for a reduction in landing rates while using barbless hooks, particularly when angling for steelhead. Finally, use of bait increased the probability that fish would be hooked in a critical location such as the esophagus or stomach. Our findings are useful for assessing trade-offs between conservation measures and harvest opportunity when defining fishing regulations in mark-selective salmon and steelhead fisheries.

Final Report and Pre-Peer Review Scientific Manuscript

Following this page, the final proviso report is provided in scientific manuscript format, intended for submission to the journal ***Fisheries Research***

Influence of angling methods and terminal tackle on survival of salmon and steelhead caught and released in the Cowlitz River, Washington

Pre-Publication Manuscript intended for peer review and publication in: ***Fisheries Research***

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Running title: Catch and release survival of salmon and steelhead

ABSTRACT

Efforts to recover depressed stocks of salmon and steelhead in North America include implementation of mark-selective recreational fisheries, whereby anglers are allowed to harvest hatchery-origin fish, but must release natural-origin fish. Catch and release (C&R) is generally thought to be an effective tool for conservation relative to traditional retention fisheries due to high survival of released adult salmon and steelhead in freshwater. However, estimates of C&R mortality are necessary for conservation and management of populations. Studies designed to estimate C&R mortality have produced highly variable results among species and size classes of fish, gear types, and environmental conditions. Moreover, previous studies suffered from considerable variability in study design, sample sizes, and associated scientific rigor, making it challenging for managers to identify mortality rates for use in specific fisheries. Therefore, crude approximations of C&R mortality are commonly used to quantify impacts to natural-origin salmon and steelhead. In addition, managers often restrict use of certain angling methods and terminal tackle that are assumed to result in higher mortality, leading to a multiplicity of different regulatory requirements with limited empirical support. We conducted a novel three-year mark-recapture study in the Cowlitz River, Washington to estimate effects of a variety of factors hypothesized to influence salmon and steelhead C&R survival using a treatment-control design. Three species of salmonids were captured and released as treatments using various angling techniques and terminal tackle. Fight time, handling time, and water temperature were also recorded during each capture event. Non-angled fish were captured in a trap and released back into the fishery to serve as controls. Logistic regression models were used to estimate the probability of recovery for both treatments and controls, where survival was estimated as the probability of recovery of treatments divided by controls. Models simultaneously evaluated the effects of covariates and isolated the effects of potential confounding variables. Recovery rates of Coho Salmon differed less than a percent between angled and non-angled fish across multiple gear types, indicating negligible effects of C&R. Angled Spring Chinook Salmon were predicted to experience 3.6% to 10.2% C&R mortality relative to non-angled control fish, depending on terminal tackle. Barbless hooks were associated with higher survival than barbed hooks for both Chinook and Coho Salmon, although differences were small for Chinook and negligible for Coho. In contrast, steelhead angled on barbed hooks were recovered at slightly higher rates than those caught on barbless hooks. We also found strong evidence for a reduction in landing rates while using barbless hooks, particularly when angling for steelhead. Finally, use of bait increased the probability that fish would be hooked in a critical location such as the esophagus or stomach. Our findings are useful for assessing trade-offs between conservation measures and harvest opportunity when defining fishing regulations in mark-selective salmon and steelhead fisheries.

INTRODUCTION

Natural-origin Pacific salmon (*Oncorhynchus sp.)* and steelhead trout (*Oncorhynchus* mykiss) abundance has declined throughout western North American (Kendall et al., 2017; National Research Council (NRC), 1996; Nehlsen et al., 1991; Welch et al., 2021) leading to widespread protection under the U.S. Endangered Species Act (ESA) (Good et al., 2005) and Canadian Species at Risk Act (Hutchings and Festa-Bianchet, 2009). Efforts to recover depressed stocks include implementation of mark-selective recreational fisheries, whereby anglers are allowed to harvest hatchery-origin fish, but must release natural-origin fish (Johnson, 2004; Zhou, 2002). Catch and release (C&R) is generally thought to have small impacts on salmon and steelhead survival in freshwater (reviewed in Raby et al. 2015) and negligibly impact population productivity (Whitney et al., 2019). However, the practice of C&R has also been shown to occasionally cause mortality of adult fish due to injury and stress, even when adopting best handling and release practices (Brownscombe et al., 2017).

Results of C&R mortality studies have varied among species and by geographic location, with the most robust studies occurring in Alaska and British Columbia, where C&R of natural-origin salmon and steelhead rapidly gained popularity in the 1980s and 1990s. Steelhead C&R mortality in the Keogh and Salmon Rivers, British Columbia was 3.4% (Hooton, 1987) and 5.4% (Lirette and Hooton, 1988), respectively. Similarly, steelhead C&R mortality in the Chilliwack River, British Columbia was 3.6% (Nelson et al., 2005). Pacific salmon studies during the same era of recreational fisheries assessment suggested higher mortality due to C&R relative to steelhead. Coho Salmon (*Oncorhynchus* kisutch) in the Little Susitna and Unalakleet Rivers, Alaska experienced 11.7% (Vincent-Lang et al., 1993) and 15% mortality (Stuby, 2002). Bendock and Alexandersdottir (1993) reported 7.6% mortality for Chinook Salmon (*Oncorhynchus tsawytscha*) released by recreational anglers in the Kenai River. More contemporary studies of C&R impacts on Pacific salmon and steelhead survival in freshwater estimated mortality rates between 1% and 12% for Chinook Salmon (Cowen et al., 2007; Fritts et al., 2016; Lindsay et al., 2004), 16% for Sockeye Salmon (Donaldson et al., 2011), and 3-5% for steelhead (Nelson et al., 2005; Twardek et al., 2018; Whitney et al., 2019).

Approximations of C&R mortality, typically inferred from disparate studies, are used by managers to estimate fishery impacts from catch and release and in turn set allowable C&R encounters in locations where impacts to natural-origin salmon and steelhead runs are a concern. Population-scale impacts are estimated by multiplying a C&R mortality rate by the number of natural-origin fish encountered in the fishery (Kerns et al., 2012). For example, in the lower Snake River, Washington steelhead fisheries are limited by a 2% impact rate on late-run steelhead, which is estimated by assuming a 10% mortality rate on all late-run steelhead caught in the fishery. Similarly, recreational angling seasons on the mainstem Columbia River, and tributaries are limited by C&R of natural-origin steelhead (WDFW 2003; NOAA 2018).

In addition to setting seasons and monitoring encounter rates, angling techniques and terminal tackle are often regulated as a conservation measure for protected stocks of salmon and steelhead (e.g. Ministry of Forests 2021). Restricting angling techniques and terminal tackle is thought to reduce C&R impacts on salmonids (Gresswell and Harding, 1997; Hooton, 2001; Muoneke and Childress, 1994) while still affording anglers an opportunity to catch fish with less harmful methods. For example, several Pacific Northwest salmon and steelhead fisheries prohibit the use of bait and/or barbed hooks and hooks with multiple points. These types of regulations are thought to improve survival of fish after release, however empirical evidence to support such claims for adult salmon and steelhead remains limited. Empirical studies of the effects of terminal tackle on salmonid C&R survival in freshwater are rare, and those that have occurred either report low sample sizes (Lindsay et al., 2004; Twardek et al., 2018) or were not conducted on anadromous salmonids (e.g. DuBois and Dubielzig 2004; DuBois and Kuklinski 2004; Bloom 2013).

The dual mandates of many management agencies to conserve salmon and steelhead runs while providing angling opportunity have led to a diverse set of rules governing the use of certain types of recreational fishing tackle in Pacific salmon and steelhead fisheries. Review of angling regulations for western North America reveals a general gradient of restrictions from low to high elevation, with the most restrictive regulations occurring at higher elevations proximate to spawning areas. A few exceptions to this general pattern are worth noting, such as barbed hook restrictions in select Lower Columbia River fisheries.

There is a need to improve the accuracy and specificity of C&R survival estimates used to manage Pacific salmon and steelhead recreational fisheries. Indeed, biased estimates of angling impacts may lead to overly constrained fisheries, or alternatively, excessive exploitation of imperiled populations. Ideally, managers would have sufficient empirical information on how C&R survival varies as a function of species, terminal gear type (e.g., bait, lures, treble hooks, and single barbless hooks), angling methods, and environmental variables, such as water temperature.

We conducted a three-year study on the Cowlitz River, Washington to evaluate the effects of angling on salmon and steelhead post-release survival. Our study aimed to address limitations of previous work by incorporating a treatment-control design, obtaining large sample sizes, and measuring numerous variables hypothesized to affect C&R mortality. Specifically, we analyzed the effects of terminal tackle and angling technique on Chinook and Coho salmon and summer and winter-run steelhead trout. We provide relative impact rates as a function of the full suite of variables measured as well as for a subset of variables under regulatory control.

METHODS

Study Area. — The Cowlitz River is a major tributary to the Columbia River draining nearly 6,500 square kilometers from the western slopes of the Cascade mountains (Serl et al. 2017; Figure 1). The river is home to anadromous fish including natural and hatchery origin Coho Salmon, spring Chinook Salmon, fall Chinook Salmon, winter steelhead trout, coastal cutthroat trout, hatchery origin summer steelhead and natural origin Chum Salmon. Occasionally other stray anadromous fish are encountered as well (i.e., Sockeye salmon). The Basin is divided into an upper and lower watershed by the Cowlitz River Hydroelectric Project, comprised of three hydroelectric dams and a large concrete weir known as the Barrier Dam. The Barrier Dam is approximately 80 kilometers upstream from the confluence with the Columbia River and prevents migrating adult salmon and steelhead from entering the Hydroelectric Project area. A trap-and-haul program transports migrating adult fish collected at the Barrier Dam upstream of the Hydroelectric Project.

Thousands of hatchery-origin (HOR) salmon and steelhead trout migrate back to the lower Cowlitz River annually, supporting a large harvest-oriented recreational fishery. Chinook and Coho Salmon are raised at the Cowlitz Salmon Hatchery (CSH), and summer and winter steelhead trout are raised at the Cowlitz Trout Hatchery (CTH). The CTH is located 11 kilometers downstream of the CSH near the mouth of Blue Creek. A high proportion of migrating adult HOR salmon and steelhead trout are captured at the Cowlitz Salmon Separator (CSS), a fish sorting facility associated with the Barrier Dam.

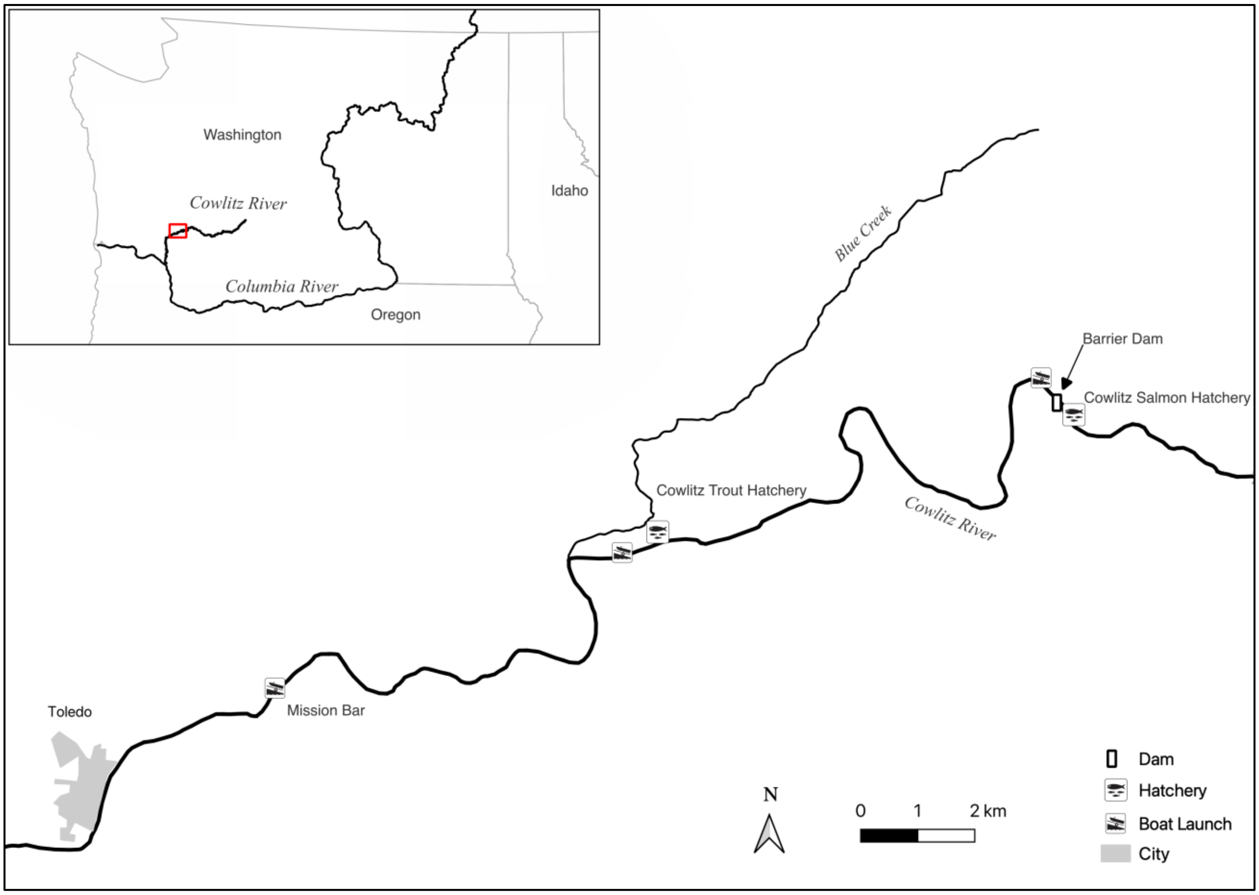

Figure 1. Study area.

Data Collection. — A treatment-control study was implemented to assess survival of angled hatchery-origin spring Chinook Salmon, Coho Salmon, and steelhead trout. Treatment fish were angled using a variety of different methods and gear types and released back into the study area, while non-angled control fish were captured at the CSS, transported downstream, and released back into the study area at several locations to disentangle release location effects from angling mortality effects on recovery. The apparent survival of both angled and non-angled fish was monitored using uniquely numbered anchor tags implanted in each treatment and control fish. Recaptured fish were primarily collected at the CSS, however recaptures were also recorded by recreational anglers (self-reporting), or during Washington Department of Fish and Wildlife (WDFW) creel and spawning surveys.

Angling occurred between the Barrier Dam and the town of Toledo from June 1, 2017 to May 31, 2020 with the majority of fish captured between the CTH and the Barrier Dam. Fish were angled from shore or by boat at least two days per week by field biologists, local fishing guides, and volunteer anglers, but all fish used for the study were captured under the supervision of project personnel who then sampled and tagged them. A variety of hook types (barbed or barbless; single or treble), gear types (bait, lures, jigs, or yarn), and angling methods (bobber, cast, side drifting, or back trolling) were used (Table 1). Gear and method selection was conducted in a non-randomized way with the intent to capture a large sample size of fish reflective of common angling practices in the region, while ensuring a reasonable variety of terminal tackle types. All captures followed legal C&R practices for salmon and steelhead in the State of Washington. Accordingly, all captured fish remained submerged in a landing net during handling. During each capture event we documented species, origin (hatchery or natural), sex, hooking location (Figure 2), hook type and size, gear type, angling method, fish condition factors (presence of fungus, percent descaling, net marks, or mammal/lamprey wounds/scars), fish length, surface water temperature, and handling and fight times. Hatchery-origin fish received a T-bar anchor tag (Floy Tag & Mfg, Seattle WA) with a unique identification number implanted on each side of the dorsal fin. Data were also recorded for fish that were hooked for at least three seconds, but not landed. Angling effort was recorded as the number of hours fished per angler.

During angling surveys, non-angled fish were concurrently captured at the CSS to serve as a control group. These fish were anesthetized by electro-anesthesia, as is standard practice at the facility for adult salmonids collected for hatchery broodstock and upstream transport, marked with anchor tags, and then transported downstream. Oxygen tanks with diffusers were used to maintain dissolved oxygen levels during transport and water temperatures and dissolved oxygen levels were continuously monitored to ensure oxygen saturation and minimal change to ambient temperatures. The locations of control fish releases were proximal to concurrent angling survey locations and included the Mission Bar, Blue Creek, or Barrier Dam boat launches. Capture data for all control and treatment fish included field survey data from the initial capture event and any subsequent recapture information including self-reporting by anglers, creel surveys, and spawning ground surveys.

Table 1. Covariates included in the full and regulatory models.

Covariate	Levels	Full Model	Regulatory Model
Treatment	Control, treatment	Yes	No
Gear type	Control, bait, lure, jig, yarn	Yes	Yes
Angling method	Control, bobber, cast, drift, backtroll	Yes	No
Barb type	Control, barbless, barbed	Yes	Yes
Hook type	Control, single hook, multi-hook	Yes	Yes
Hook location	Control, critical, non-critical	Yes	No
Hook removed	Control, yes, no	Yes	No
Fork length	Continuous	Yes	No
Fight time	Continuous	Yes	No
Handling time	Continuous	Yes	No
Water temperature	Continuous	Yes	No

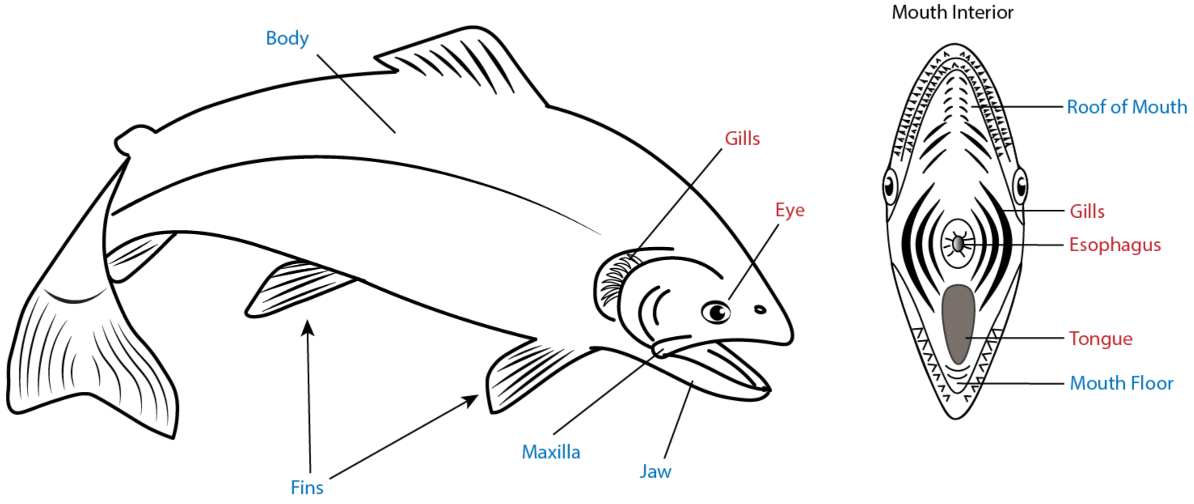

Figure 2. Critical (red) and non-critical (blue) anatomical hooking locations.

Analytical Approach.

We used a hierarchical Bayesian mixed-effects modeling approach to quantify Coho Salmon, Chinook Salmon, and steelhead trout mortality due to C&R angling by comparing the predicted recapture probability between the control and treatment groups using a logit-link regression model. Survival of treatment fish relative to controls was estimated by dividing the inverse-logit transformed predicted recovery rate of treatments by that of controls. Within this approach, we examined the influence of the method and gear types used for angling and other covariates collected at the time of capture on recapture probability and survival. Models also contained random-effects parameters including a random intercept accounting for unique release events and factor spline terms for the year and day of year a fish was captured or released and the location. The generalized regression formula is given by:

Equation 1:

$$R = f(\boldsymbol{Xb} + D_{d,y} + L_{m,y,r} + \gamma_k + \varepsilon_{ijk})$$

where *R* is the recapture response variable (whether a fish was recaptured or not) distributed Bernoulli with a logit-link function *f*. Predicted survival was a function of the product of an *n* row (observations) by *k* column (parameter) design matrix $\boldsymbol{X}$, consisting of categorical and continuous covariates, and a vector $\boldsymbol{b}$ of corresponding regression coefficients, including a global intercept. In addition to these linear continuous and categorical effects, the model included terms $D_{d,y}$ and $L_{m,y,r}$, where subscripts included the day *d*, year *y*, river mile *m*, and run type (summer or winter run for steelhead) *r*. These were smoothing terms that used factor spline basis functions and were used to estimate non-linear effects of possible nuisance variables to control for possible spatial and temporal variability and confounding of recovery probabilities. Date effects *D* estimated day of year effects within each study year and location effects *L* estimated release location effects as a function of river mile of release within each study year independently for each run type (summer and winter) for steelhead. The model also included a random effect γ_k with mean zero and variance σ_s^2 to account for the repeated measures variance associated with each unique release event *k*, and finally, the *iid* residual error term ε_{ijk}, which was the difference between the logit-transformed prediction and the Bernoulli response.

Separate models were constructed for Coho Salmon, spring Chinook Salmon, and steelhead trout. Coho and spring Chinook models did not include the location by year factor spline because > 99% of the releases of control and treatment fish occurred in the vicinity of the Barrier Dam boat launch, and consequently the negligible amount of data from other release locations was excluded from the analysis for these species to eliminate the need to estimate spatial random effects. Spring chinook control fish were only available in 2018 therefore modeling only included that single year. Steelhead models did not include control fish, and inferences were therefore limited to the relative recovery rates within the treatment arm of the study. Despite attempts to release control fish in the steelhead study, the downstream location of the steelhead hatchery in the Cowlitz River at Blue Creek relative to the salmon hatchery adjacent to our main point of recapture at the Barrier Dam (Figure 1) led to unanticipated confounding of the steelhead controls and thereby precluded their use in the analysis. For each species, we fit a full model along with a reduced 'regulatory model' that included parameters commonly regulated in C&R fisheries (Table 1). Full models were used to rank the relative importance of covariates on recapture probability, however many of these covariates, such as fight time and hook location, are not under regulatory or angler control (within the study or in a C&R fishery). Therefore, we also fit a model that restricted variables to those under angler and regulatory control to predict C&R mortality as a function of variables under resource manager control.

Because a fully randomized study design was not intended, we applied a regularized horseshoe prior on the vector of $\boldsymbol{b}$ coefficients, excluding the global intercept (Piironen and Vehtari, 2017). This method was chosen for its robustness to (1) correlation between angling methods, gear selection, and angler success that led to small sample sizes for some combinations of gear types and methods, and (2) the assumption that not all covariate levels will have a strong influence on mortality, and 3) a desire to identify a sparse and regularized model that evaluated the relative strength of support for all covariate effects with maximum explanatory power, without either over-fitting, or constructing numerous models comprised of factorial combinations of predictor variables that would be difficult to distinguish with classical model selection approaches (Hooten and Hobbs, 2015).

To facilitate direct comparison of categorical and continuous covariates, continuous covariates were standardized by two standard deviations as described in Gelman (2008). Models were constructed using the 'brms' package in the program R (Bürkner, 2017; R Core Team, 2022), that leverages the 'mgcv' package (Wood, 2017) to calculate basis functions for the random intercept and spline terms. Spline terms were given the default hyperparameters (e.g., penalty order, knot numbers and locations) from mgcv. Model predictions for recapture probability were calculated using the 'brmsmargins' package (Wiley, 2022). Model outputs were assessed using convergence trace plots, Gelman-Rubin Rhat values (Gelman and Rubin, 1992), inspection of random-effects spline curves, and the posterior distributions of covariate coefficients along with associated 95% highest density intervals (HDI).

For Coho Salmon, which had much greater treatment and control sample sizes than other species, we conducted two additional Bayesian regression analyses that examined the factors that influence critical hooking location and handling time. In part this was because hooking location and handing time cannot be controlled during fish capture events but may influence C&R mortality (Bartholomew and Bohnsack, 2005; Lindsay et al., 2004). The critical hook location model treated whether or not a fish was hooked in a critical location as a Bernoulli-distributed response using a logit link to an additive regression function with covariates including angling method and gear type which were given a regularized horseshoe prior similar to the hooking mortality models (eq. 1). The handling time model used a gaussian-distributed response with a horseshoe prior on critical hooking location, barb or barbless hook, and single or multi-hook type predictor covariates.

RESULTS

From June 1, 2017, to May 31, 2020, more than 7,200 rod-hours resulted in angling 2,700 salmon and steelhead trout, including non-target species (Table 2). Of these fish, 2,014 were landed after being hooked, including 1,562 hatchery-origin salmon and steelhead. Landing rates for all target species were higher when angling with barbed hooks compared to barbless hooks.

Concurrent with angling surveys, 3,791 fish were trapped at the CSS, tagged, and released into the lower Cowlitz River as control fish. Most of these fish were Coho Salmon (n = 1,096) and summer (n = 1,832) and winter steelhead trout (n = 781). 82 spring Chinook Salmon were released as control fish. Returns of spring Chinook in 2019 and 2020 were not sufficient to allow for control fish releases.

The majority of treatment and control fish were recaptured at the CSS (84.5%) and by recreational anglers (13.1%). Other minimal sources of recapture included spawning surveys (<1%) and out-of-basin fish traps (<1%). The proportion of fish recaptured by each method was similar across species, with the exception of summer steelhead trout; of which 62.5% were recaptured at the CSS and 35.2% by anglers. This is likely due to prolonged exposure of summer steelhead trout to angling pressure downstream of Blue Creek. Initial recaptures of treatment fish occurred between 1 and 97 days after capture (median = 18 days; Figure 3).

The hooking mortality analysis excluded angled fish that were not tagged, and were consequently not available for recapture (e.g., natural origin fish and fish that were not landed). Additionally, control fish that were subsequently recaptured during angling surveys were recorded as control recaptures, then converted to treatment fish and released. Our analysis only considered the first recapture event for individual fish that were recaptured multiple times. All recapture events were defined as capture events that occurred at least 24 hours after the initial release. Seven treatment Coho were not included in the analysis due to insufficient sample sizes for the gear and methods used during their capture. Control fish that were released upstream of the study area were also removed from the analysis.

Full and regulatory models were fit for Coho and Chinook data and effects of covariates on recovery rates and survival relative to controls are reported. For steelhead, model results describe variation in recapture probability only (no inference relative to controls) as a result of the removal of the control group. For all models, the horseshoe prior led to β coefficient posterior distributions with clear shrinkage towards zero and long tails when posterior samples were further from zero, as expected. Therefore, the density of posterior distributions was greatest near zero and covariates with evidence for influence on C&R mortality had posterior distributions with strong negative skew. Random effects intercept and spline terms indicated some variation in recapture probability attributed to unique surveys, and day and year of capture or release for treatment and control fish, and for steelhead, capture or release rkm for years by run type. Spline functions were consistent within species across models.

The Coho full model did not provide clear evidence for covariate effects on recapture probability (Table 3). Handling time and critical hooking location covariates were weakly associated with reduced Coho recapture probability; the probability of a negative effect was 0.61 and 0.58, respectively (Table 3). Median relative mortality predictions for angled fish relative to non-angled from the regulatory model were less than 1%, and did not indicate significant differences due to gear, barbs, or single and multiple hook types (Table 4; Figure 5).

The Coho handling time and critical hook location regression analyses provided some insight to factors that affect handling time duration and the probability of hooking Coho in a critical location. In the handling time model, barbed hooks had the greatest magnitude of effect, with a >0.9 probability that barbs increased handling time and a median predicted increase of 3 seconds (95% HDI: -0.6 - 8.5). Critical hook location and multi-hooks were predicted to increase handling time to a lesser degree (Table 5). The critical hook location model revealed significant differences in the probability of hooking Coho in a critical location for some angling method and gear type combinations (Figure 4). The median probability of critical hook locations while casting with jigs and lures were 1.9% and 5.1%, respectively, while using a bobber with bait resulted in a critical hook probability of 19%.

Spring Chinook models provided stronger evidence for a treatment effect. Lower recovery probabilities were weakly associated with barbed hooks relative to non-barbed, critical hooking locations relative to non-critical hooking locations, and multiple hooks relative to single hooks, however all of these associations had probabilities far below statistical significance standards (e.g., 95%). The overall median predictions of relative mortality from the regulatory model ranged from 3.6% to 10.2% depending on gear type, barbed or barbless hook, and single or muti-hook type (Table 7; Figure 4). In all cases, the 95% HDI for estimates of relative mortality included zero.

Steelhead models did not provide any evidence for variation in recapture rates among angled fish. Similarly, recapture probabilities predicted from the regulatory model did not display significant variation for gear, barb, and single or multiple hook type combinations (Table 8; Figure 6).

Table 2. Summary of angling surveys. Totals include NOR and HOR fish and control fish that were converted to treatment fish. CPUE does not include recaptures angled by the public or unknown species.

Species	**Number Hooked**	**Number Landed**	**Landing rate with barbs**	**Landing rate without barbs**	**CPUE (fish landed / hour)**
Chinook Salmon	411	345	.871	.782	0.293
Coho Salmon	1503	1270	.871	.802	0.992
Summer-run steelhead	182	127	.765	.571	0.057
Winter-run steelhead	384	268	.735	.617	0.103
Sockeye Salmon	3	3	1.00	--	--

Table 3. Coho Salmon full model outputs. Covariate coefficients are relative to non-angled control fish.

Covariate	Mean	Median	95% HDI, lower	95% HDI, upper	Probability of negative effect
Handling time	-0.034	-0.0006	-0.282	0.0447	0.6135
Critical hook location	-0.0441	-0.0004	-0.3548	0.1246	0.5768
Bobber with bait	-0.0257	-0.0003	-0.2202	0.1017	0.5748
Barbed hook	-0.0024	-0.0001	-0.0679	0.0483	0.5255
Hook removed	-0.0011	0	-0.0628	0.0563	0.5088
Angling effect	-0.0017	0	-0.0727	0.0666	0.5035
Multi-hook	-0.0033	0	-0.0964	0.0679	0.5032
Single hook	0.0012	0	-0.0651	0.0685	0.4958
Backtrolling with bait	0.0047	0	-0.1088	0.1008	0.4948
Hook left in fish	-0.0019	0	-0.1062	0.0893	0.494
Barbless hook	0.0023	0	-0.0681	0.0661	0.4852
Casting a lure	0.0005	0	-0.061	0.0694	0.4835
Drifting with bait	0.0064	0	-0.111	0.0881	0.4808
Casting a jig	0.0032	0.0001	-0.0554	0.0734	0.469
Fork length	0.0046	0.0001	-0.0443	0.0758	0.465
Non-critical hook location	0.0072	0.0001	-0.0625	0.0825	0.4582
Temperature	0.0054	0.0001	-0.0624	0.0743	0.4572
Fight time	0.0109	0.0002	-0.0608	0.1191	0.4475

Table 4. Predictions of Coho Salmon survival, relative to non-angled control fish, based on gear, barb, and hook types from the associated regulatory model.

Gear	Hook	Barb or barbless	Mean	Median	95% HDI, lower	95% HDI, upper
Bait	Single	Barbless	0.9976	0.9999	0.9592	1.0339
		Barbed	0.9964	0.9998	0.9580	1.0292
	Multi	Barbless	0.9966	0.9998	0.9466	1.0332
		Barbed	0.9955	0.9996	0.9495	1.0336
Jig	Single	Barbless	1.0021	1.0002	0.9771	1.0341
		Barbed	1.0010	1.0001	0.9753	1.0303
Lure	Single	Barbless	1.0008	1.0001	0.9740	1.0302
		Barbed	0.9997	1.0000	0.9716	1.0262
	Multi	Barbless	0.9998	1.0000	0.9700	1.0392
		Barbed	0.9987	0.9999	0.9661	1.0317

Table 5. Predicted effects on Coho Salmon handling time, in seconds, produced from the handling time model (mean handling time = 95 seconds).

Covariate	Mean	Median	95% HDI, lower	95% HDI, upper	Probability of positive effect
Barbed hook	3.28	3.0	-0.58	8.52	0.91
Critical hook location	1.34	0.40	-2.00	7.14	0.69
Multi-hook	0.99	0.28	-2.36	6.26	0.67

Table 6. Spring Chinook Salmon full model outputs. Covariate coefficients are relative to non-angled control fish.

Covariate	Mean	Median	95% HDI, lower	95% HDI, upper	Probability of negative effect
Angling effect	-0.2609	-0.0204	-1.3995	0.127	0.7048
Barbed hook	-0.0799	-0.0046	-0.6174	0.1854	0.6242
Casting a lure	-0.1101	-0.0023	-0.9708	0.3045	0.593
Multi-hook	-0.1092	-0.003	-0.9867	0.2876	0.5918
Hook removed	-0.0385	-0.0016	-0.463	0.2317	0.575
Non-critical hook location	-0.0504	-0.0019	-0.508	0.1907	0.5738
Bobber with bait	-0.0343	-0.001	-0.5184	0.2996	0.5538
Hook left in fish	-0.0378	-0.0009	-0.4749	0.2226	0.5512
Single hook	-0.0324	-0.0009	-0.5277	0.2724	0.551
Temperature	-0.0263	-0.0008	-0.3822	0.236	0.5508
Critical hook location	-0.0188	-0.0004	-0.3993	0.2193	0.5295
Barbless hook	-0.0047	0	-0.2763	0.239	0.502
Handling time	0.0051	0.0001	-0.2496	0.2263	0.488
Fork length	0.0053	0.0003	-0.2354	0.1827	0.474
Fight time	0.028	0.0011	-0.1623	0.332	0.4472
Angling effect	-0.2609	-0.0204	-1.3995	0.127	0.7048
Barbed hook	-0.0799	-0.0046	-0.6174	0.1854	0.6242
Casting a lure	-0.1101	-0.0023	-0.9708	0.3045	0.593

Table 7. Predictions of spring Chinook Salmon survival, relative to non-angled control fish, based on gear, barb, and hook types from the associated regulatory model.

Gear	**Hook**	**Barb or barbless**	**Mean**	**Median**	**95% HDI, lower**	**95% HDI, upper**
Bait	Single	Barbless	0.9266	0.9643	0.6946	1.0580
		Barbed	0.8858	0.9132	0.6403	1.0429
Lure	Multi	Barbed	0.8129	0.8980	0.3397	1.0593
	Single	Barbed	0.8508	0.9251	0.4222	1.0979

Table 8. Predictions of steelhead trout recapture probability based on gear, barb, and hook types from the associated regulatory model.

Gear	**Hook**	**Barb or barbless**	**Mean**	**Median**	**95% HDI, lower**	**95% HDI, upper**
Bait	Single	Barbless	0.5185	0.5201	0.4036	0.6211
		Barbed	0.5206	0.5230	0.4116	0.6252
	Multi	Barbless	0.5152	0.5174	0.4009	0.6300
		Barbed	0.5173	0.5197	0.4039	0.6313
Jig	Single	Barbless	0.5165	0.5184	0.4051	0.6163
		Barbed	0.5186	0.5208	0.4102	0.6163
Lure	Single	Barbless	0.5179	0.5201	0.4045	0.6287
		Barbed	0.5200	0.5219	0.4040	0.6238
	Multi	Barbed	0.5167	0.5199	0.4036	0.6337
Yarn	Single	Barbless	0.5097	0.5130	0.3944	0.6154
		Barbed	0.5117	0.5151	0.4041	0.6182
	Multi	Barbed	0.5085	0.5127	0.3951	0.6252

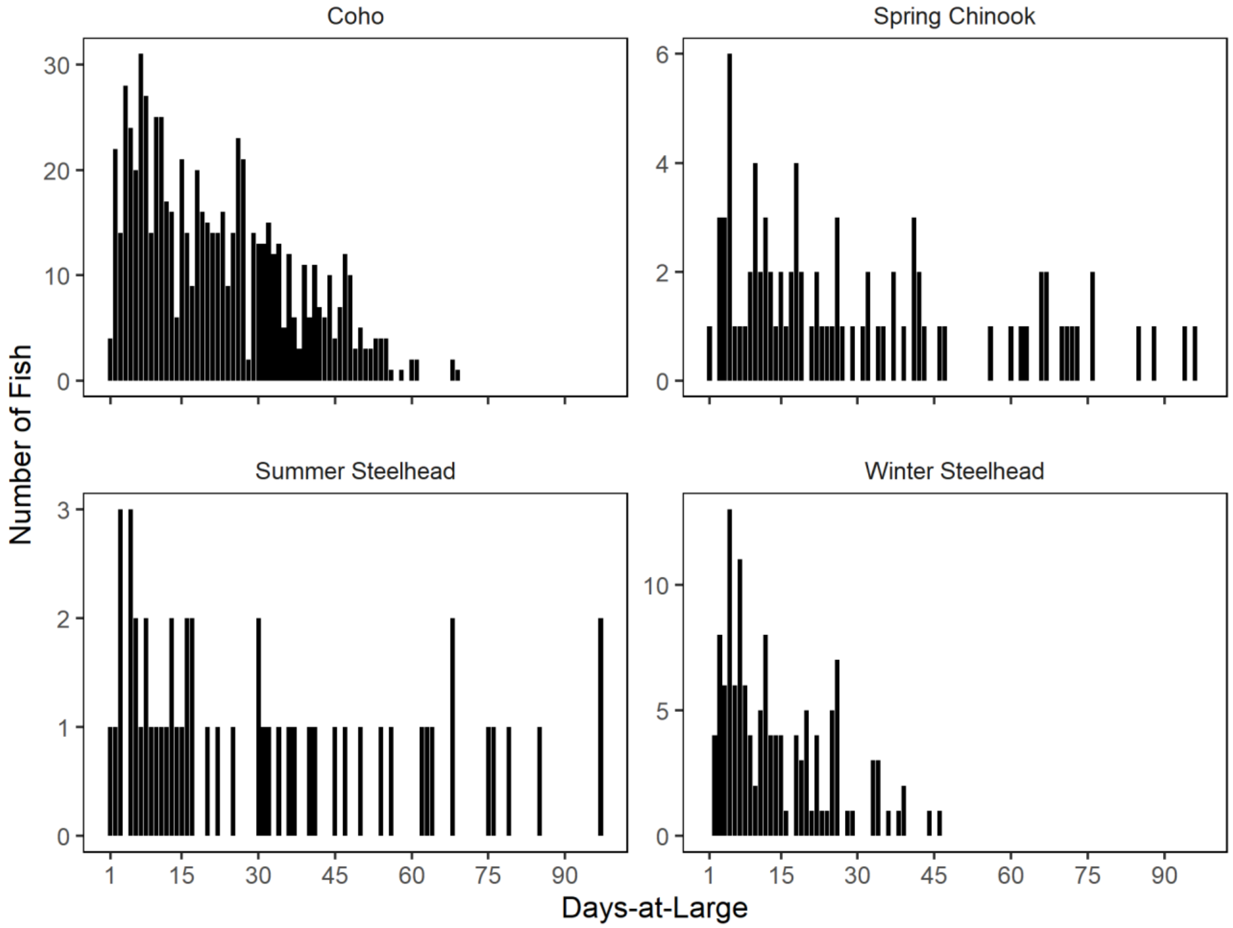

Figure 3. Frequency of the number of days between capture and initial recapture of treatment fish by species and run type.

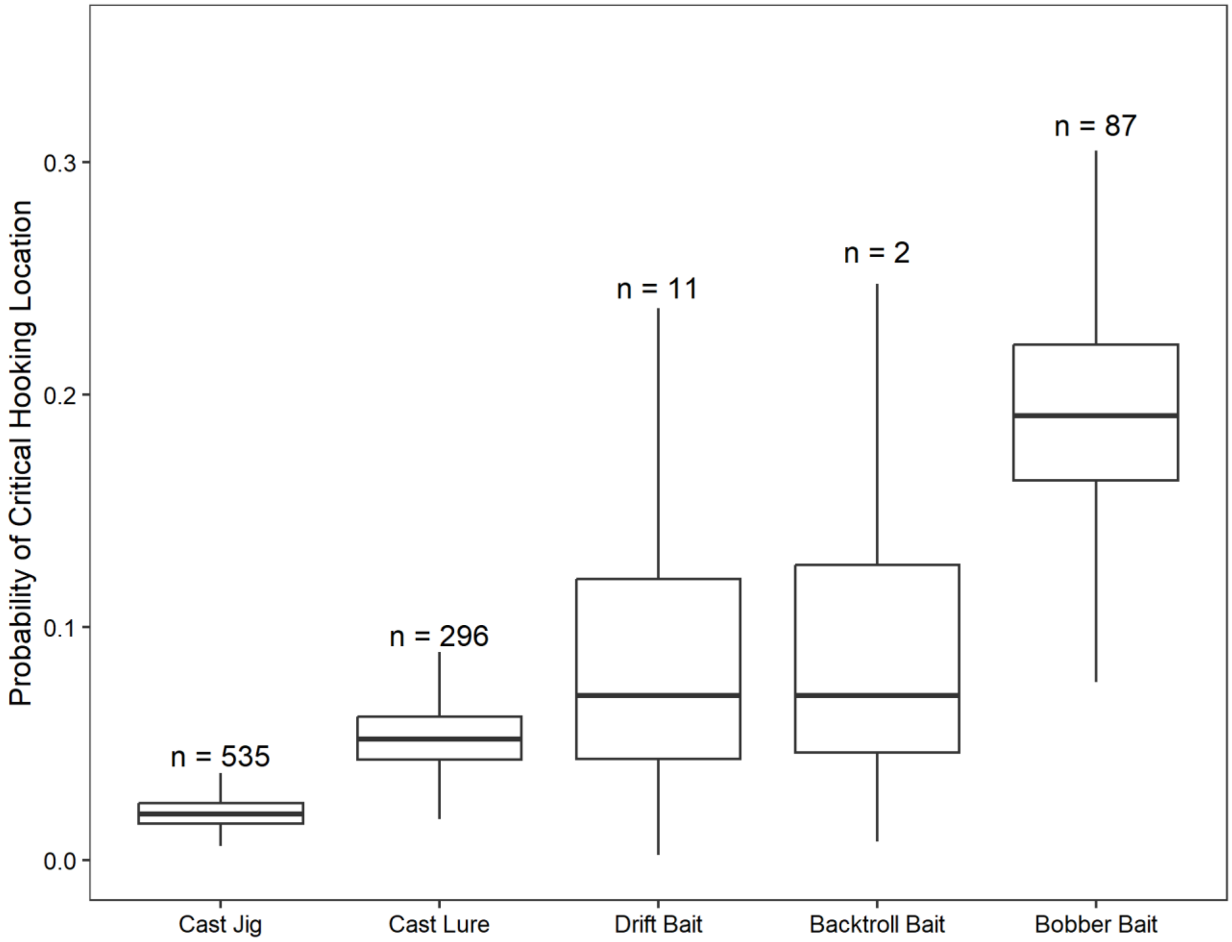

Figure 4. Critical hook probability for Coho Salmon by combinations of angling method and gear type. Values above boxplots are the sample sizes observed for each combination.

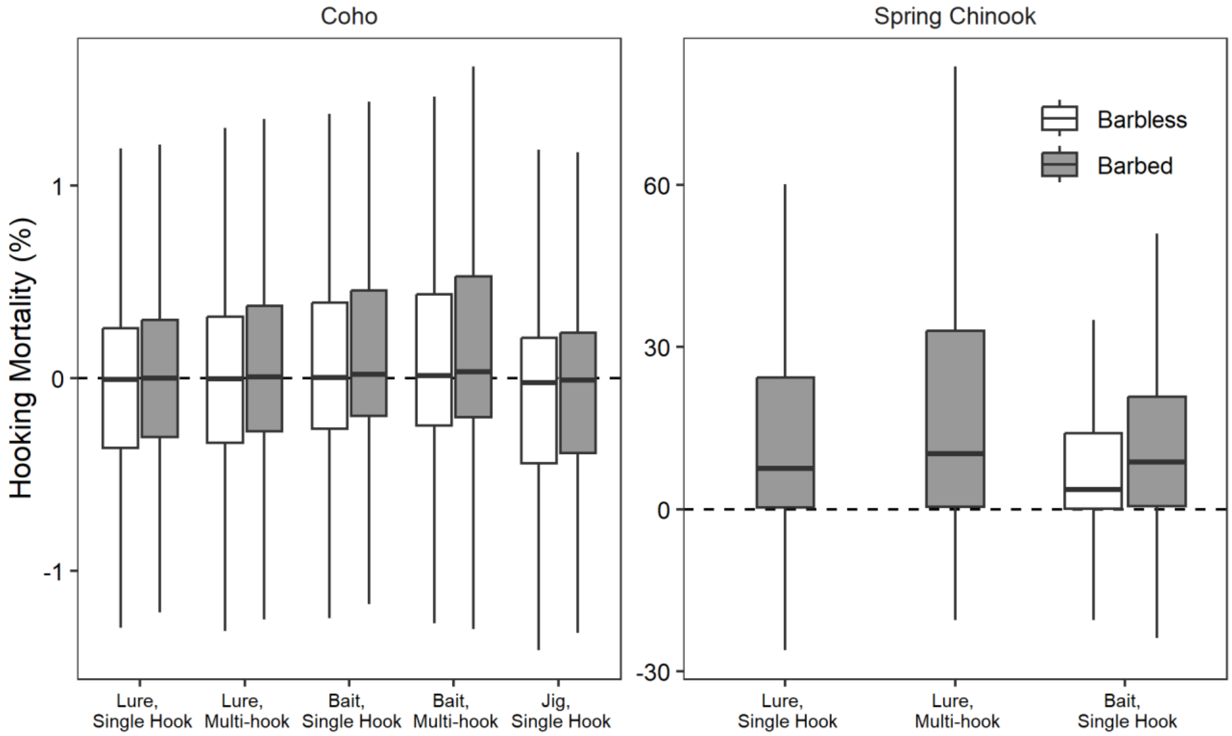

Figure 5. Predicted hooking mortality for Coho Salmon and spring Chinook Salmon, given the combinations of gear, single or multi-hook types, and barbed or barbless hooks that were observed during the study.

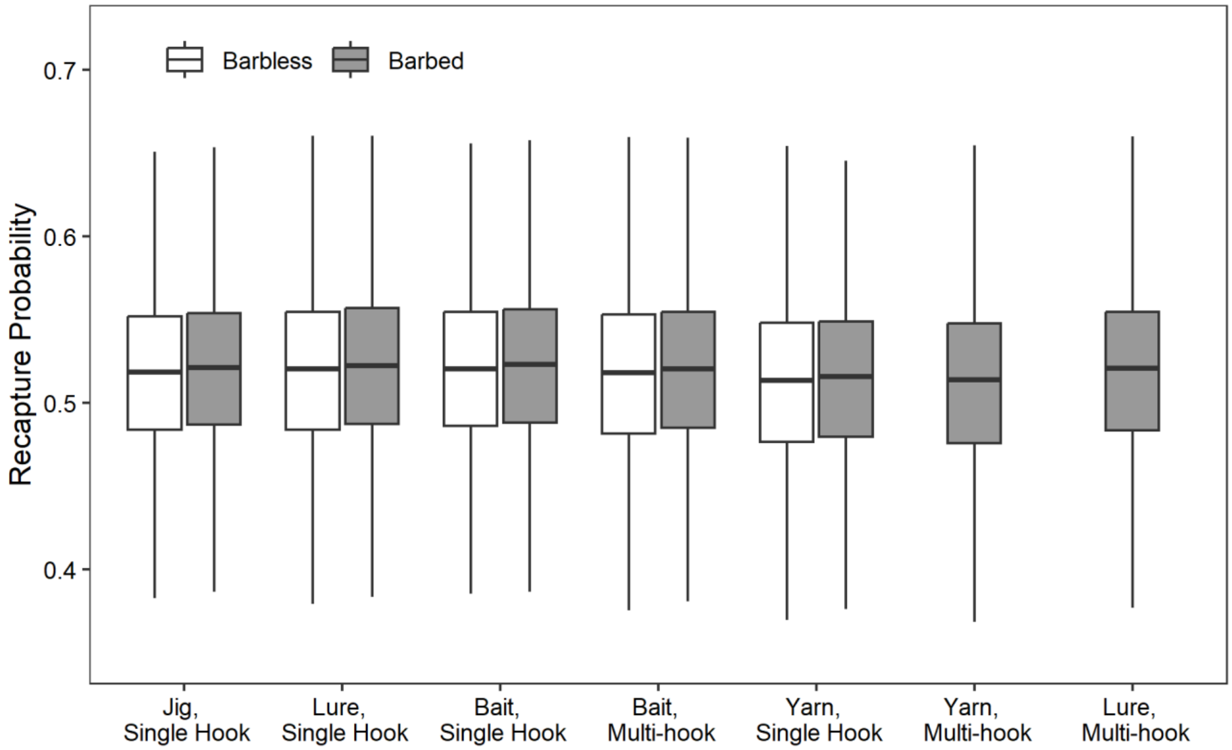

Figure 6. Predicted variation in recapture probability for angled steelhead trout, given the combinations of gear, single or multi-hook types, and barbed or barbless hooks that were observed during the study.

DISCUSSION

Existing fish capture facilities, abundance of hatchery-origin fish, and anadromous fish species diversity made the Cowlitz River an ideal location for implementing a C&R survival study. Previous research has been conducted on select recreational fisheries in Alaska, British Columbia, and the Pacific Northwest, but these evaluations were typically limited to a single species. Moreover, few studies of salmon and trout C&R survival were designed to quantify the influence of terminal tackle and angling methods. In addition to estimating C&R survival of anadromous salmonids, our dataset proved useful for examining effects of terminal gear type and fishing methods, fight time and handling time, hook location, and water temperature.

Coho Salmon survival was high after C&R with no clear evidence for differences in recapture rates for control and treatment fish. This suggests C&R recreational fisheries that primarily target Coho Salmon with lures and jigs should be expected to have negligible impacts on prespawning survival. It was unclear whether Coho Salmon fisheries that rely on bait should be expected to increase prespawning mortality because few Coho in our database were angled with bait. However, we did find secondary evidence that terminal tackle may influence Coho Salmon survival. Specifically, use of bait increased the probability of hooking fish in critical locations, and use of barbed hooks slightly increased handling time. We found stronger evidence for angling effects on Spring Chinook Salmon, which were predicted to experience 3.6% to 10.2% C&R mortality relative to non-angled control fish, depending on terminal tackle.

Regulation of terminal tackle is commonly employed to reduce impacts of C&R. Therefore, we tested the efficacy of purported conservation measures, such as restricting use of barbed hooks. Lower recovery probabilities were weakly associated with barbed hooks relative to non-barbed hooks. Our results corroborate previous meta-analyses that indicate negligible differences in survival for adult anadromous fish angled with barbed and barbless hooks (Schill and Scarpella, 1997), but differ from other studies that have reported barbless hooks result in higher post-release survival in Coho Salmon (Gjernes et al., 1993) and non-anadromous trout (Taylor and White, 1992). We found some secondary evidence that use of barbed hooks increased handling time, which has been associated with higher mortality in Atlantic Salmon recreational fisheries (Thorstad et al., 2003).

Although salmon and steelhead caught on barbed and barbless hooks were recaptured at nearly indistinguishable rates, we did find strong evidence for substantial differences in landing rates between the two hook types. Angling with barbless hooks, especially when targeting steelhead, resulted in lower landing rates. This was an important finding that could be useful to managers when assessing trade-offs between conservation and fish retention opportunity within recreational fisheries. For example, restricting anglers to use of barbless hooks in harvest-oriented fisheries may substantially impact harvest rates without providing a significant conservation benefit. Conversely, there may be no downside to restricting barbed hooks in C&R only fisheries where the intent is to minimize impacts on pre-spawning survival and all fish are required to be released.

Across all captures, our data indicate that angling with bait should be expected to reduce survival of C&R salmon and steelhead as compared to other gear types. Consistent with previous studies (see Bartholomew and Bohnsack 2005; Lindsay et al. 2004), this appears to be due to an increased probability of hooking fish in critical locations while using bait. The effect of bait on critical hooking location and recapture probability of C&R fish was subtle, but consistent for all species.

Our results corroborate previous findings that increased surface water temperature at capture negatively affects steelhead survival ((Bartholomew and Bohnsack, 2005; Bentley and Rawding, 2016), although the effect was quite small, likely because temperatures in the Cowlitz River remain within the physiological optima for salmonids. This is because reservoirs in the Basin moderate river temperature conditions such that peak summer temperatures rarely exceed 16 degrees Celsius. We expect that temperature effects are stronger in rivers where water temperatures approach and surpass critical stress thresholds for salmonids (e.g., 18 degrees Celsius or higher).

We did not evaluate effects of angling on resident or juvenile salmonid survival, which may explain differences between our findings and those of some previous studies. We hypothesize this may be because smaller resident and juvenile fish are more vulnerable to mortality due to serious injury from handling and hook removal. Small fish need to recover and continue actively feeding, whereas adult salmon and steelhead only need to survive to spawn, possibly lessening the importance of some types of injuries. Given differences in life-history and size of resident and anadromous salmonids relative to typical terminal angling gear, it is reasonable to expect that specific types of terminal tackle, such as barbed hooks, may impact resident and juvenile salmonid mortality but negligibly influence adult anadromous salmonid mortality.

This research addressed a key shortcoming of many previous studies by using controls. However, control fish were imperfect representatives of the non-angled fish population. Capture at the CSS and transport of control fish, which differed from the handling of angled fish, could have positively biased estimates of survival for angled fish by an unknown amount due to unmeasured impacts of this additional handling. However, we believe these impacts were minimal because the trap and haul operations routinely assess mortality for hatchery broodstock and upstream transported salmon and steelhead and these impacts are thought to be negligible. Ideally, salmon and steelhead would have been marked as outmigrating juveniles and detected entering the study area as adults. This would have afforded us an unbiased group of non-angled control fish similar to the fish survival estimation methods described by Skalski et al. (2010). However, this method was not practical given our resource and timeline constraints.

Our study was designed to address mortality as the primary experimental endpoint. However, sublethal impacts of angling on anadromous salmon and steelhead remains a primary management concern. For example, changes in reproductive success, migratory behavior, or rates of iteroparity could have significant biological consequences. While difficult to assess, these types of sublethal impacts, if they occur because of angling, may be more consequential to population productivity than effects of angling on prespawning survival, and warrant further evaluation.

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