Catch and Release as a Management Strategy for Steelhead in British Columbia

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Abstract

In British Columbia the most frequent application of catch and release has been on heavily used steelhead streams in the populated southwestern management regions. Seven years of data compiled since the first broad scale implementation of catch and release on Vancouver Island in 1980 indicated that the regulation was effective in reversing declining catch trends but that recovery from the sharp initial reductions in licence sales and angler days was slow and mostly related to the recent availability of hatchery steelhead. Hooking mortality associated with catch and release angling was low and survival through spawning for released fish was normal.

Introduction

British Columbia with its thousands of miles of coastline contains a dazzling array of steelhead streams. Each year over 200 streams sustain some recorded angler effort and catch (Steelhead Harvest Analysis 1968-1987) while at least that many more support steelhead but are not fished. Streams range from smaller outer coast winter and/or summer steelhead producers to the large interior tributaries of major river systems such as the Fraser, Skeena, Nass, Stikine and Taku. Many of these latter tributaries—the Kispiox, Babine, Sustut, and Thompson—are world renowned for their exceptionally large, wild summer steelhead.

By fisheries management policy the steelhead streams of British Columbia are categorized as hatchery, augmented, or wild according to their natural ability to produce wild steelhead. With one exception the 22 augmented streams and 4 hatchery streams are located in the heavily populated southwest corner of the province. Wild streams, which clearly dominate the total provincial picture occur throughout the coast from the U.S. Border to southeast Alaska and in the interior (Fig. 1).

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A common feature of a large majority of British Columbia's steelhead streams is their low productivity. The smolt yield capacity is generally well below levels experienced in more southerly environments such as the Columbia basin, the historic center of steelhead abundance. Regulations governing steelhead harvest in British Columbia must therefore be relatively restrictive. Catch and release has become a major management tool to deal with low productivity streams and the cumulative effect on such waters of competing habitat uses, heavy sportfishing pressure and/or high exploitation by commercial and Indian food fisheries. Generally these streams are located in southwestern British Columbia in Management Regions 1 and 2 (Fig. 1). Most of the provincial data base associated with evaluation of catch and release has been compiled in Region 1 (Vancouver Island). For this reason the present report will focus on the Vancouver Island experience.

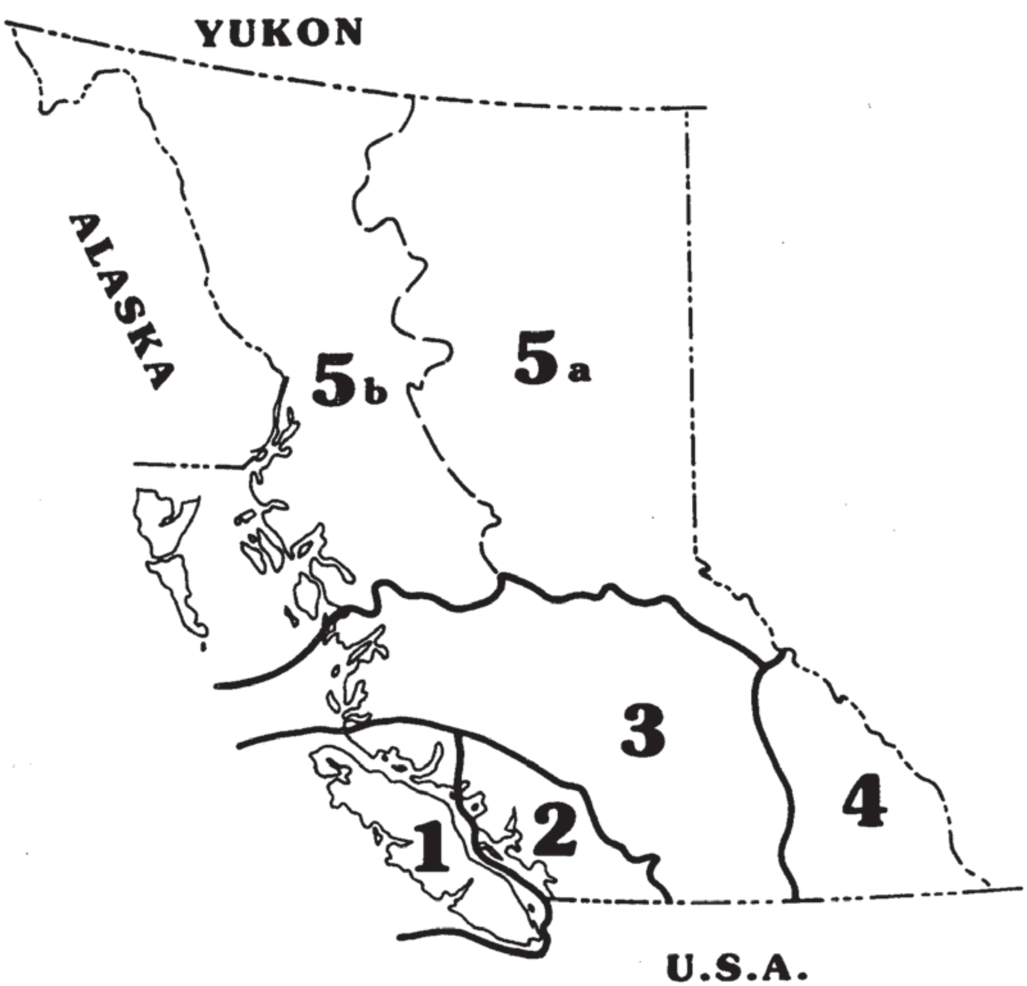

Figure 1. British Columbia resource management regions. Steelhead regions include 1 (Vancouver Island), 2 (Lower Mainland), 3 (Thompson-Cariboo) and 5b (Skeena).

The Vancouver Island Study Area

The Steelhead Fishery

Vancouver Island, a large coastal island adjacent to the heavily populated lower Fraser River valley, contains approximately 35% of the provincial total of streams which sustain measurable steelhead angler effort and catch annually. In recent years the Island has supported 20% of the days fished, 25% of the wild steelhead catch, and more than 60% of the hatchery steelhead catch for all of British Columbia (Steelhead Harvest Analysis, 1968-1987). In the 1986-87 season 5000 steelhead licences were sold to Island residents and angler days totalled 57,000.

Stream specific steelhead catches on Vancouver Island range from tens to thousands. Recently, more than half of the annual catch of 50-60,000 steelhead has occurred in only five streams and approximately 90% in not more than ten. The days fished pattern was similar. Hatchery steelhead are available in 11 streams but in most of these only since the early 1980's. Wild steelhead dominate the total angler catch.

Regulations History

Regulations governing wild steelhead harvest were uniformly liberal across all of British Columbia from the earliest days of provincial fisheries management until the late 1970's. At that time, under the sponsorship of the Salmonid Enhancement Program, many first ever investigations of steelhead stock size and exploitation revealed the necessity for major reductions in daily and season catch limits. On Vancouver Island these reductions were scheduled to take effect in 1980. Further restrictions included catch and release only for all summer steelhead streams and a monthly limit to avoid chronic over-harvest of the early component of the winter steelhead run (Table 1).

Coincident with the agenda to introduce reduced catch limits in April 1980 came a disastrous winter steelhead season in 1979-80. This necessitated an emergency catch and release regulation which was subsequently included in the formal regulations from 1980-84 (Table 1). During the latter four years, hatchery programs were coming on line rapidly and anglers were provided the opportunity to harvest marked hatchery fish throughout the year. By 1985 hatchery production goals were realized and wild steelhead harvest was eliminated entirely.

Table 1. Summary of major regulation changes governing wild steelhead harvest on Vancouver Island streams, pre - 1959 to present.

Years	Steelhead Harvest Quotas			
	Per Day	Per Month	Per Year	Per River
Pre - 1959	3			
1959 - 1961	3		40	
1962 - 1976	2		40	
1977 - 1979	2		20	10
1980 - 1984*	1	2	5	
1985 - Present	0	0	0	

*Further restriction included wild steelhead release Dec. 1 - Mar.1.

Evaluation of the Regulations

The objective of the wild steelhead catch and release regulation on Vancouver Island was to stabilize and, hopefully, reverse a steadily declining catch trend. Data were available from annual mailed questionnaire sampling of licences to compare effort and catch success in the "pre" and "post" catch and release years. These data provided a basis for assessing the efficacy of the regulation.

A common criticism of catch and release was that it was "unsafe" because steelhead subjected to such treatment would die or be weakened to a point where successful reproduction would not occur. To investigate these issues a study was designed to determine the mortality rate among steelhead caught and released on popular terminal tackle and to assess the spawning success of these fish relative to a control group. The research was conducted at Keogh River, an intensively monitored stream on northern Vancouver Island. Complete results of the Keogh study will be reported separately but important features are included here. A further indication of the consequences of catch and release was available from records on steelhead angled for brood stock for hatchery programs.

Results and Discussion

Angler Participation and Catch

The immediate response of anglers to the wild steelhead catch and release, first imposed mid-way through the 1979-80 winter steelhead season, was a 50% reduction in days fished (Fig. 2). In the following licence year (ending in 1981) there was a similar decline in the number of licences sold (Fig. 2). The number of days fished remained at historic lows for three years after which a strong upward trend developed. By 1985 the pre-catch and release angler days total was surpassed (Fig. 2). Licence sales, though increasing remained 20% below the pre-regulation level (Fig. 2). These data indicated that under catch and release angling effort increased from an average of 10 days per licencee to 12.

Retrospective analysis of the circumstances surrounding initiation of catch and release in 1980 left a clear impression that the need to acquaint licencees and the supporting services industry with the full rationale for catch and release was underestimated. If a professional public relations capability had been employed to sell the catch and release concept, the observed declines in licence sales and days fished would likely have been far less dramatic.

Licence sales and days fished over the 1983-87 period was undoubtedly influenced by the rapid growth of the hatchery steelhead program. The extent of this influence as opposed to a growing acceptance of catch and release is unknown but evidence presented below suggests the availability of hatchery steelhead was the dominant factor.

The number of wild steelhead retained by Vancouver Island anglers displayed a declining trend for more than a decade before any catch and release restrictions (Fig. 3). This was due, in part, to growing perceptions of some anglers that their ability to harvest fish had been underestimated, that the regulations were too liberal, and that steelhead abundance was declining. The total catch of wild steelhead over the 1971-79 period strongly supported a declining abundance theory (Fig. 4).

In the years 1980-84 the seasonal catch and release regulations reduced the wild steelhead kill to approximately one third of the preceeding three-year average. This was followed by a further decline after 1985 when year round catch and release came into effect (Fig. 4). The fact that some wild steelhead kill was reported in those years when harvest was illegal probably resulted from errors in catch reporting, misidentification of hatchery fish and/or deliberate non-compliance.

Total catch of wild steelhead increased sharply during the catch and release period and remained well above previous peaks (Fig. 4). Tagging studies revealed that a substantial portion (>30%) of the increase could be attributed to repeat captures (Hooton and Lirette 1986; Hooton 1979; unpublished Fish and Wildlife Branch data). It must be noted, however, that

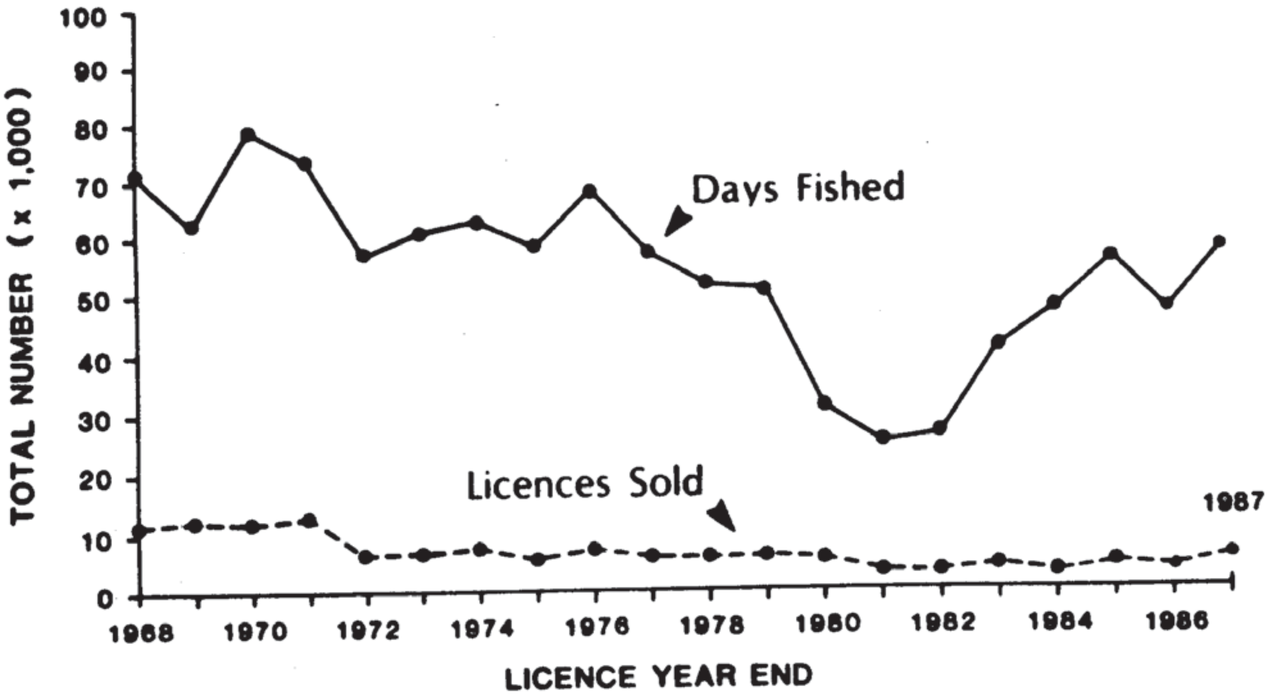

Figure 2. Number of days fished and steelhead angling licences sold, Vancouver Island, 1968 through 1987.

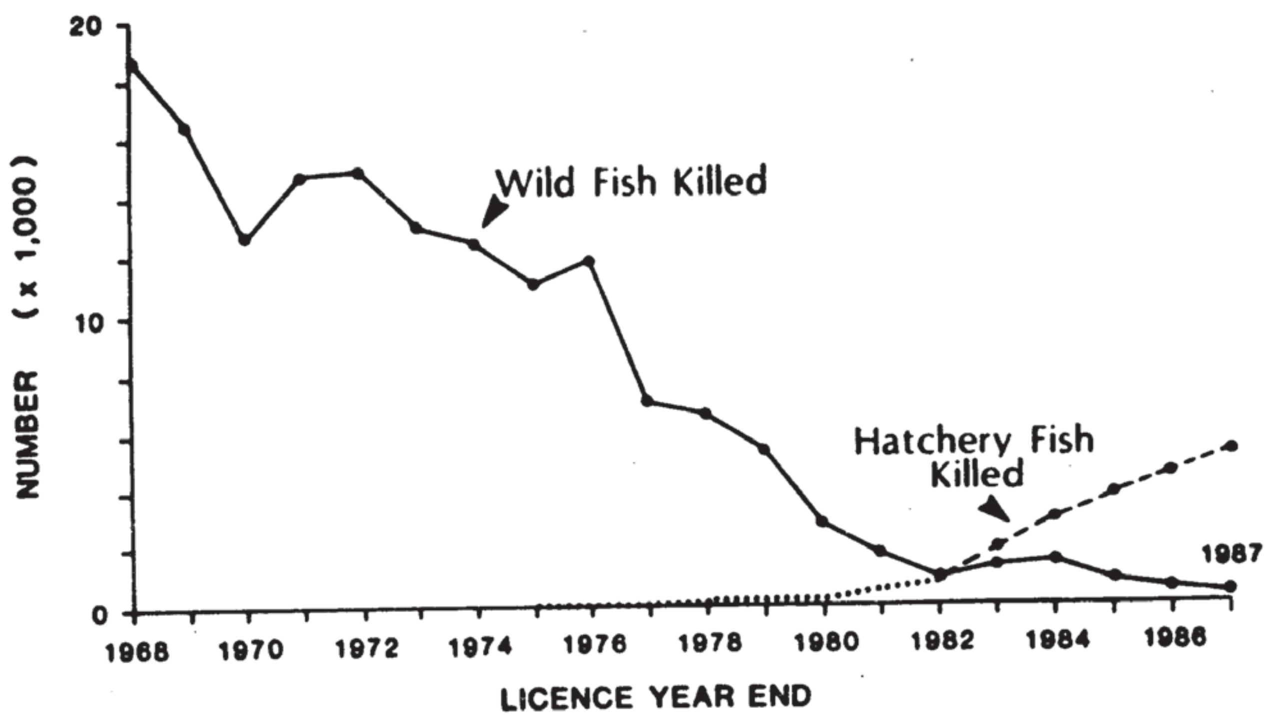

Figure 3. Number of wild and hatchery steelhead killed by anglers on Vancouver Island streams, 1968 through 1987.

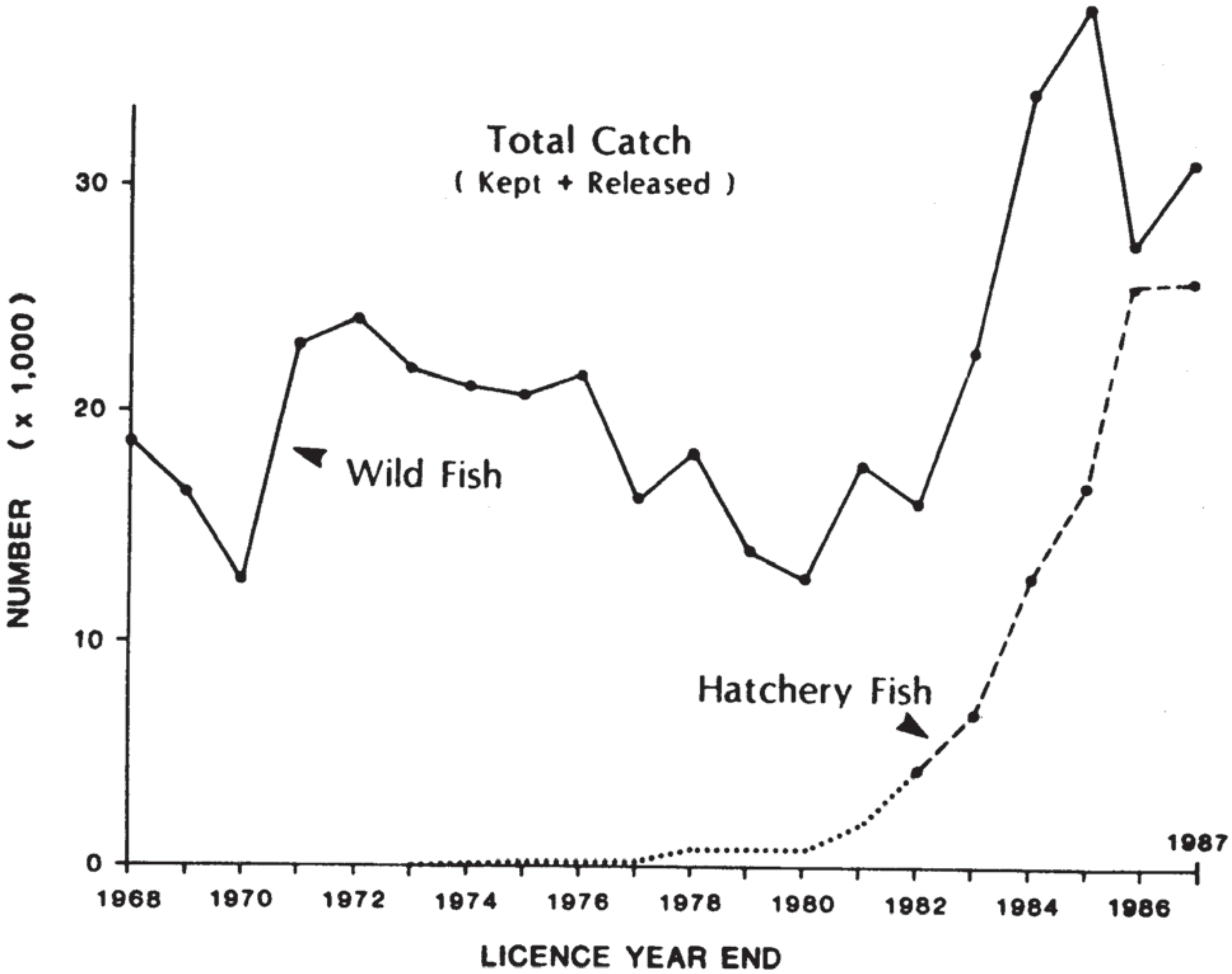

Figure 4. Total angler catch (kill and release) of wild and hatchery steelhead on Vancouver Island streams, 1968 through 1987.

catches were also responsive to an unusually high abundance of wild steelhead in 1984 and 1985, a phenomenon that was observed elsewhere in British Columbia and thoughout the steelhead range.

The response in wild steelhead recruitment from increased escapements which followed catch and release has not been measured and, in fact, could not be separated from environmental influences and the contribution of hatchery adults which spawned naturally. However, the subjective interpretation of the author is that wild steelhead recruitment (i.e. abundance and catch) will continue to fluctuate annually in response to these other variables but at a substantially higher level than would have occurred in the absence of catch and release.

Angler preference studies conducted on Vancouver Island in the mid 1970's determined that, under the circumstances of the day (i.e. liberal catch limits, relatively stable total catch, little hatchery production) catch and release was not a popular regulations option (Hooton 1982). Empirical evidence from the catch and release period confirmed that attitude despite changes in wild steelhead stock status and increasing hatchery steelhead availability. At Gold River, the most prolific wild steelhead only stream in the region, angler days were declining during the 1976-79 period (Fig. 5). The decline continued through 1980 when catch and release came into effect. However, despite catch and catch per unit effort figures which reached record highs in the 1983-87 period, angler days remained well below previous levels (Fig. 5). In contrast, the experience on four popular steelhead streams where anglers had the option of fishing for both hatchery and wild steelhead, the number of angler days and the percent of the total Vancouver Island steelhead angler days increased steadily through the pre and post 1980 period as the supply of hatchery steelhead increased to target levels (Fig. 6). Clearly, the pattern has been one of relatively low and stable angling effort on "wild" streams and deflection of anglers toward "augmented" steams where harvest opportunity remained.

Hooking Mortality and Spawning Success

The opinions that released steelhead die or do not spawn successfully, commonly heard from critics and opponents of catch and release, were refuted by data compiled from hooking mortality studies. Among 3715 steelhead angled on conventional tackle (bait, barbed hooks) to provide brood stock for hatchery programs, only 127 (3.4%) mortalities occurred (Table 2). A large majority of these fish subsequently survived the stress of frequent handling, transport, and lengthy confinement in hatchery facilities before maturing and being spawned. Virtually the entire Vancouver Island (and elsewhere in British Columbia) hatchery steelhead program was built around and continues to operate with these procedures.

At Keogh River where hooking mortality was studied more rigorously, similarly high survivals were noted. Among 336 steelhead angled on various combinations of popular terminal gear (Table 3) the mortality for the combined samples was 5.1% (Table 4). Use of natural bait produced higher

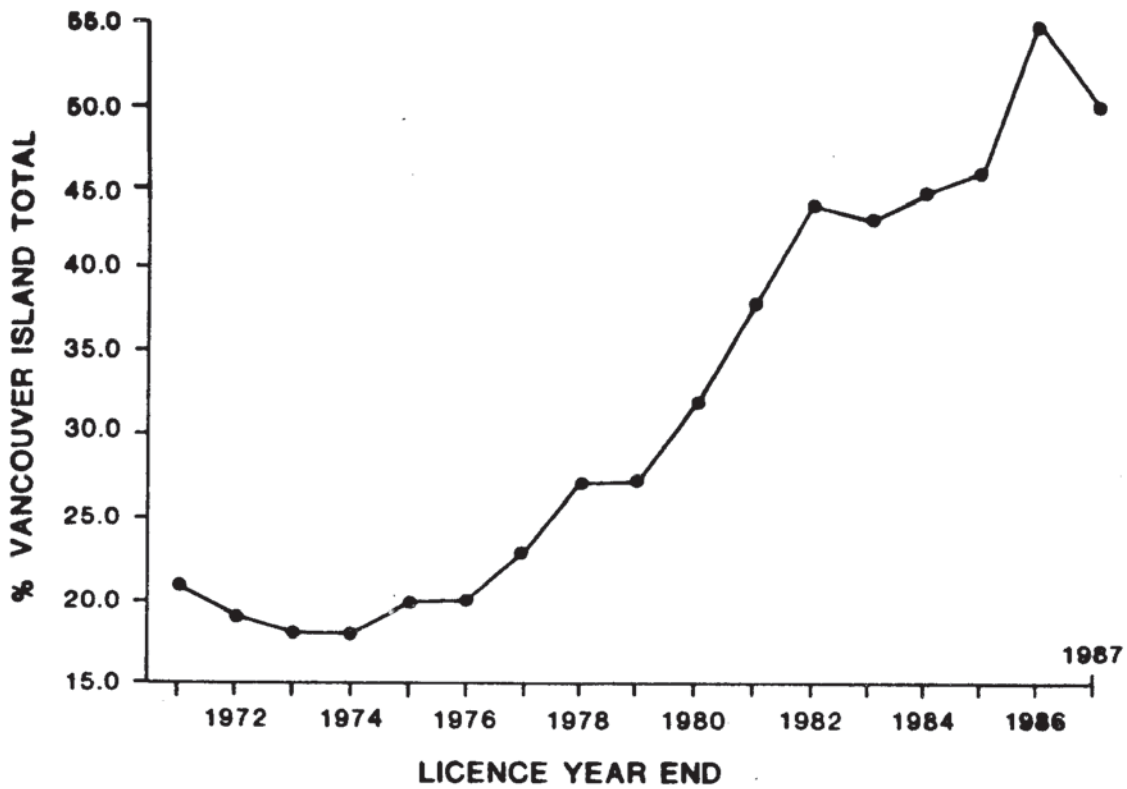

Figure 5. Percent of total Vancouver Island steelhead angler days expended on four popular hatchery steelhead streams, 1971 through 1987.

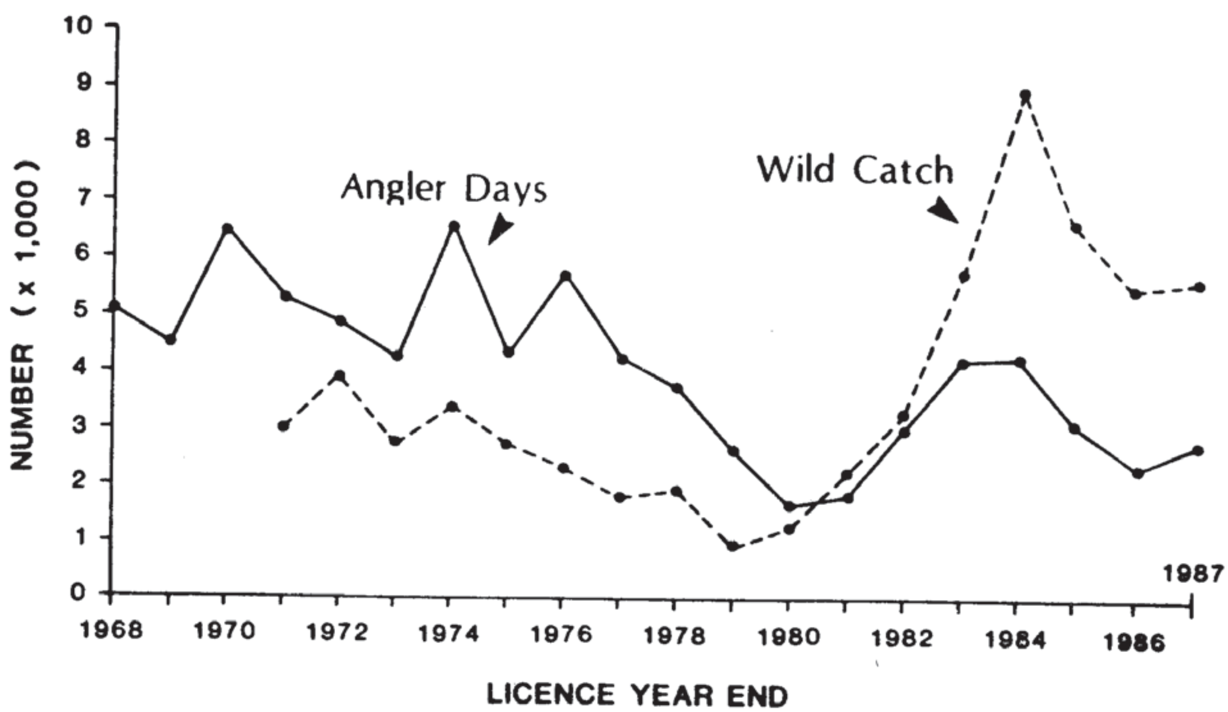

Figure 6. Number of steelhead angler days and total wild steelhead catch (kill plus release), Gold River, 1968 through 1987.

mortality (5.6%) than did artificial lures (3.8%) (Table 4). Also, mortality while using barbed hooks was higher (7.3%) than for barbless hooks (2.9%) regardless of whether bait or artificial lure was employed (Table 4). Analysis of the number of steelhead landed per hour fished on each gear combination indicated that bait was approximately 60% more efficient than artificial lure. This figure was probably minimal, however, because a high proportion of the angling sessions commenced with artificial lures and the number of catchable fish was likely much reduced before bait was employed.

Table 2. Stock specific hooking mortality among steelhead angled for brood stock purposes, Vancouver Island, 1981 - 1987.

Stock	Years of Record	Number of Steelhead Angled	Number (Percent) Hooking Mortalities
Cowichan	7	509	16 (3.1)
Englishman	5	240	9 (3.8)
Heber	1	70	3 (4.3)
Gold	1	30	0 (0)
Nanaimo	7	378	7 (1.9)
Puntledge	7	481	9 (1.9)
Salmon	6	464	27 (5.8)
San Juan	2	49	3 (6.1)
Somass	7	1174	43 (3.7)
Tsitika	7	320	10 (3.1)
All	N/A	3715	127 (3.4)

Table 3. Number of steelhead captured on various terminal gear types, Keogh River hooking mortality study, 1985 and 1986.

Year	Gear Type*								
	BB	BA	NBB	NBA	All	BB + NBB	BA + NBA	BB + BA	NBB + NBA
1985	48	26	56	0	130	104	26	74	56
1986	51	40	77	38	206	128	78	91	115
1985 + 1986	99	66	133	38	336	232	104	165	171

* BB = barbed hook, bait
BA = barbed hook, artificial
NBB = barbless hook, bait
NBA = barbless hook, artificial

Table 4. Number (percent) of hooking mortalities on various terminal gear types, Keogh River, 1985 and 1986.

Year	Gear Type								
	BB	BA	NBB	NBA	ALL	BB + NBB	BA + NBA	BB + BA	NBB+ NBA
1985	6(12.5)	2(7.7)	2(3.6)	0(0)	10(7.7)	8(7.7)	2(7.7)	8(10.8)	2(3.6)
1986	3(5.9)	1(2.5)	2(2.6)	1(2.6)	7(3.4)	5(3.9)	2(2.6)	4(4.4)	3(2.6)
1985 +1986	9(9.1)	3(4.5)	4(3.0)	1(2.6)	17(5.1)	13(5.6)	4(3.8)	12(7.3)	5(2.9)

The survival through spawning of angled and released Keogh River steelhead was similar to that of steelhead which were captured at a weir at the same location 400 m. upstream from the ocean. The number of steelhead caught immediately downstream from the weir, tagged, released immediately upstream, and later trapped as emigrating post-spawners represented 27.5% of the available population. This was only 5.4% lower than the recovery rate for fish which were not angled (Table 5). This margin may have been attributable to additional handling stress endured by the angled fish.

Comparison of the degree of hooking injury with mortality rates revealed, not unexpectedly, that mortality was highest among fish which sustained severe blood loss when the hook pierced or tore a major blood vessel (Table 6). An instructive feature of the data was that, despite extensive blood loss, 47% of the most seriously injured fish recovered and were released in what appeared to be a healthy condition (Table 6). Interestingly, while the number of fish in the most severe injury groups (i.e. categories 2 and 3) was small, their recovery as post-spawners did not differ substantially from the least injured fish. Again this refuted claims that caught and released steelhead were effectively lost from the population.

Conclusions

1. Catch and release is an effective mechanism for maintaining angling opportunity without negatively impacting stock recruitment.

2. A significant proportion of the angling public does not participate in purely catch and release fisheries, especially in the absence of any organized, advance promotion of such regulations.

3. Blanket catch and release restrictions are not necessary on some relatively healthy and/or remote wild steelhead streams (stocks) on Vancouver Island. However, relaxation of the existing regulation on a small number of streams would concentrate anglers and increase harvest beyond tolerable limits, thus re-creating the circumstances which demanded catch and release initially. The management strategy on these exceptional streams must therefore be rigidly enforced stock specific harvest quotas.

4. Catch and release management of wild steelhead stocks will become an increasing biological necessity in British Columbia as competing user groups strengthen their claims to the resource, as the stream habitat base is eroded by the inexorable forces of population growth and resource development, as angler efficiency increases, and as lobby pressures demand. The Fish and Wildlife Branch will be required to play an advocacy role in this evolutionary process.

Table 5. Number (percent) of hooking mortality study (HMS) and non-hooking mortality study (NHMS) steelhead recovered as emigrating post-spawners, Keogh River, 1985 and 1986.

Year	HMS Fish Recovered as Kelts	NHMS Fish Recovered as Kelts
1985	25 (22.3)	56 (24.03)
1986	59 (30.6)	403 (34.7)
1985 + 1986	84 (27.5)	459 (32.9)

Table 6. Number (percent) of hooking mortalities among steelhead of various hook injury categories and the percent of individuals of each category recovered as emigrating post-spawners, Keogh River, 1985 and 1986 data combined.

Hook Injury*	Fish Landed	Hooking Mortalities (%)	Potential Spawning Population	Number (Percent) Post-Spawners Recovered
1	257	0(0)	247	51(20.6)
2	49	1(2.0)	44	7(15.9)
3	30	16 (53.3)	14	4(28.6)
All	336	17 (5.1)	305	84(27.5)**

* 1=Superficial wound, no blood loss
2=Moderate wound, some blood loss but no major blood vessel ruptured
3=Severe blood loss associated with rupture of major blood vessel

** Includes 22 HMS kelts which had lost tags.

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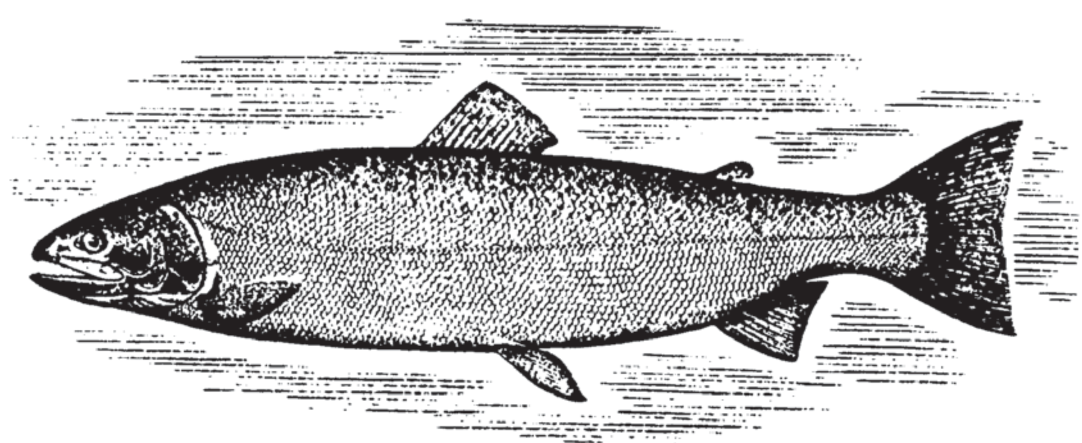

Influence of angling methods and terminal tackle on survival of salmon and steelhead caught and released in the Cowlitz River, Washington

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Full length article

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ABSTRACT

Efforts to recover depressed stocks of salmon and steelhead trout 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 angling (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. Studies designed to estimate C&R mortality have produced highly variable results among species and size classes of fish, gear types, and environmental conditions. 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 control-treatment design. Three species of anadromous salmonids were captured and released as treatments using various angling techniques and terminal tackle. Fight time, handling time, and water temperature were recorded during each capture event. Non-angled fish were captured in a trap and released back into the fishery to serve as controls. 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 experienced 3.6–10.2 % 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 trout angled on barbed hooks were recovered at slightly higher rates than those caught on barbless hooks. We also found evidence for a reduction in landing rates when angling using barbless hooks. Finally, use of bait increased the probability that salmon 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.

1. Introduction

Natural-origin Pacific salmon (*Oncorhynchus* spp.) and steelhead trout (*O. 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

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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 (*O. 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 tshawytscha*) 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 (*O. nerka*; 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 C&R and in turn set allowable fish 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 (National Oceanic and Atmospheric Administration NOAA, 2018; Washington Department of Fish and Wildlife (WDFW), 2003).

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).

The dual mandates of many management agencies to conserve salmon and steelhead runs while providing angling opportunity has led to a diverse set of rules governing 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.

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 control-treatment 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.

2. Methods

2.1. Study area

The Cowlitz River is a major tributary to the Columbia River draining nearly 6500 square kilometers from the western slopes of the Cascade mountains (Serl et al., 2017; Fig. 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 (*O. clarkii)*, hatchery-origin summer steelhead trout and natural origin Chum Salmon (*O. keta*). Occasionally other stray anadromous fish are encountered as well (e.g. 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 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 hatchery-origin salmon and steelhead trout are captured at the Cowlitz Salmon Separator (CSS), a fish sorting facility associated with the Barrier Dam.

2.2. Data collection

A control-treatment 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 in order 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 city 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

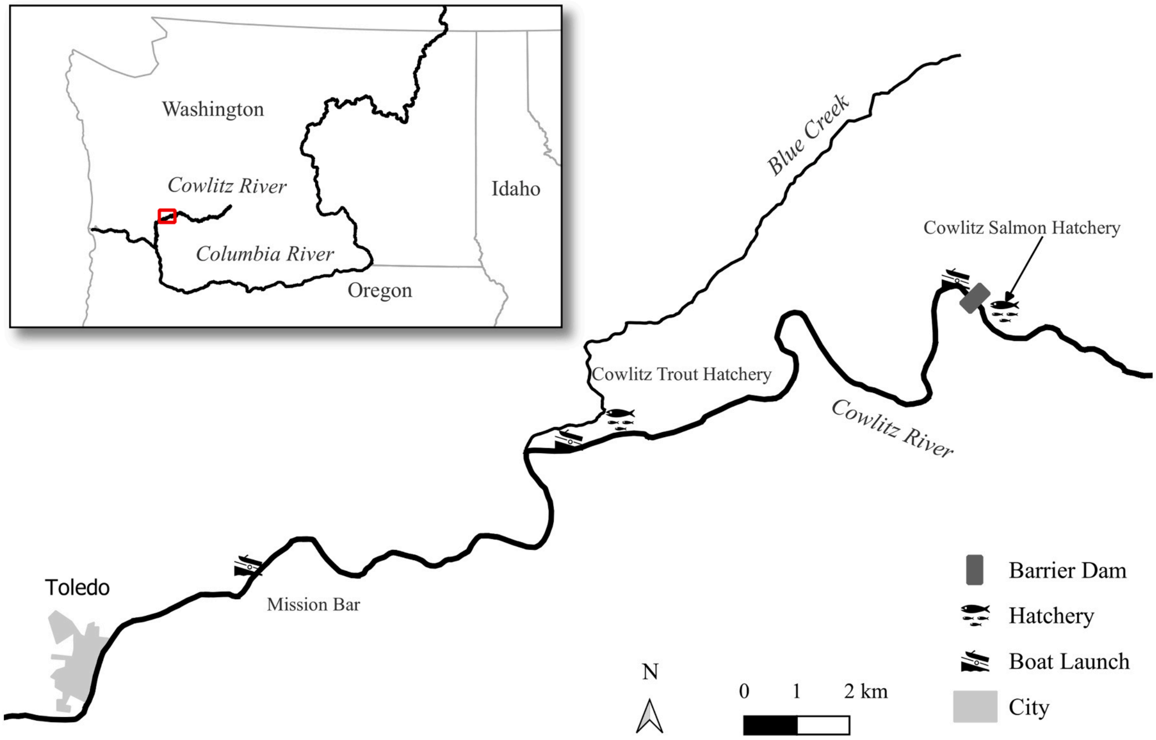

Fig. 1. Map of the study area. Angling occurred in the Cowlitz River between the city of Toledo and the Barrier Dam. Control fish were initially captured at the Cowlitz Salmon Separator, located adjacent to the Barrier Dam, and were subsequently released.

guides, and volunteer anglers. Project personnel conducted tagging and data collection of treatment fish and supervised all angling activities. 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 intended 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 and data collection. During each capture event, we documented species, origin (hatchery or natural), sex, hooking location (Fig. 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 two t-bar anchor tags (Floy Tag & Mfg, Seattle WA) with unique identification numbers–one 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.

Non-angled fish were concurrently captured at the CSS to serve as a control group. These fish were anesthetized by electroanesthesia, 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 (Tacoma Power, 2006). Oxygen tanks with diffusers were used to maintain dissolved oxygen levels during transport. Water temperatures and dissolved oxygen levels were continuously monitored to ensure oxygen saturation and minimal change to ambient stream temperatures. The locations of control fish releases were proximal to angling survey locations and included the Mission Bar, Blue Creek, or Barrier Dam boat launches (Fig. 1). 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 model and the subset included in regulatory model.

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

2.3. 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. A Bayesian regression analysis was also conducted to examine the effect of barbed and barbless hooks on landing rates. 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), we conducted two additional Bayesian regression analyses that examined the factors that influence critical hooking location and handling time. These latter analyses only included Coho Salmon, which had large treatment and control sample sizes compared to other species in this study.

Models were constructed using the 'brms' package (Bürkner, 2017) in the program R (R Core Team, 2023). Model outputs were assessed using convergence trace plots, Gelman-Rubin Rhat values (Gelman and Rubin, 1992), inspection of random-effects spline curves, and the

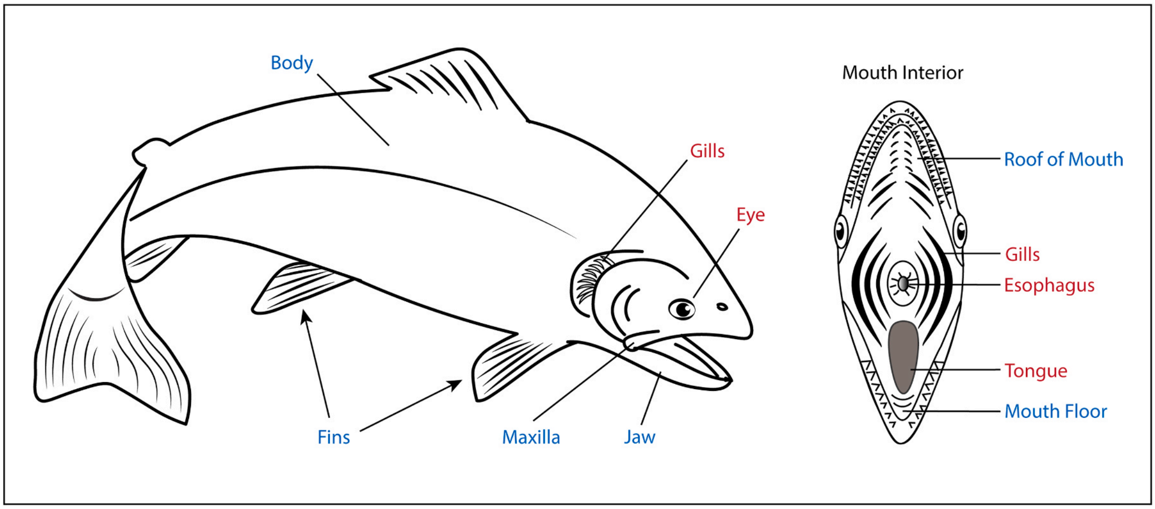

Fig. 2. Critical (red) and non-critical (blue) anatomical hooking locations.

posterior distributions of covariate coefficients along with associated 95 % highest density intervals (HDI). Model predictions for recapture probability were calculated using the 'brmsmargins' package (Wiley, 2022).

2.3.1. Catch and release mortality

Coho Salmon, Chinook Salmon, and steelhead trout mortality due to C&R angling was quantified 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 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 and survey 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:

$$R = f(\boldsymbol{Xb} + D_{d,y} + L_{m,y,r} + \gamma_k + \varepsilon_{ijk}) \quad (1)$$

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 smoothing terms $D_{d,y}$ for the estimated date effect as a function of day of year d and study year y, and $L_{m,y,r}$ for the estimated release location effect as a function of river kilometer m, study year y, and run type (i.e., summer and winter steelhead) r. These smoothing terms used factor spline basis functions and were used to estimate non-linear effects of possible nuisance variables and control for spatial and temporal variability. D is the estimated date effect as a function of day of year and study year. L is the estimated release location effect and is a function of river kilometer, study year, and run type (i.e., summer and winter 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 independent and identically distributed 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 Salmon and Spring Chinook Salmon 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. Consequently, Coho Salmon and Spring Chinook Salmon released at other locations were excluded from the analysis to eliminate the need to estimate spatial random effects. Spring Chinook Salmon control fish were only available in 2018 therefore modeling only included that year.

The 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 and were then considered initial captures of treatment fish and released. Recaptured fish that had been formerly converted from control to treatment were recorded as treatment recaptures. Our analysis only considered the first recapture event (within a treatment group) for individual fish that were recaptured multiple times. All recapture events were defined as capture events that occurred at least 24 h 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.

Steelhead models did not include control fish, and inferences were therefore limited to relative recovery rates within the treatment component of the study. Despite attempts to release steelhead for use as controls, the downstream location of the steelhead hatchery in the Cowlitz River at Blue Creek caused control fish to avoid our main point of recapture at the Barrier Dam (Fig. 1); this confounded our ability to recapture steelhead control fish and we were unable to devise an analytical solution to address this bias.

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 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) 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). The horseshoe prior was parameterized with the default one degree of freedom of the student-t prior of the local shrinkage parameters and an expected ratio of non-zero to zero coefficient values of 0.5.

To facilitate direct comparison of categorical and continuous covariates, continuous covariates were standardized by two standard deviations as described in Gelman (2008). After standardizing continuous covariates for treatment fish, control fish continuous covariates were set to zero and categorical covariates were designated as the reference level 'control'. Basis functions for the random intercept and spline terms were calculated using the brms package which leverages the 'mgcv' package (Wood, 2017). Spline terms were given the default hyperparameters (e.g., penalty order, knot numbers and locations) from mgcv. Models were run with four chains for 2000 iterations, and 1000 burn-in samples.

2.3.2. Landing probability

The landing probability models for angled Coho Salmon, Spring Chinook Salmon, and steelhead trout were constructed using a similar additive Bayesian regression framework. The response, fish landed or not landed, was treated as a Bernoulli-distributed variable with a logit-link function. All fish successfully identified after being hooked were included in the analyses. Covariates for hook barb type (barbed or barbless) and number of hooks (single or multi-hook) were included with the same regularized horseshoe prior as the C&R mortality model. A random intercept parameter for unique surveys and spline terms for year and time of year did not noticeably affect model fit and were therefore not included. Models were run with four chains of 2000 iterations and 1000 burn-in samples.

2.3.3. Hook location

The critical hook location model for angled Coho Salmon used a similar Bayesian additive regression model framework, and treated whether or not a fish was hooked in a critical location as a Bernoulli-distributed response with a logit-link function. Critical hook location was predicted using a single categorical covariate that described all observed angling method and gear type combinations (Table 1). The same regularized horseshoe prior parameterization as the C&R mortality models was used on this covariate (Eq. 1). Random intercepts for unique surveys and spline terms for year and time of year did not noticeably affect model fit and were therefore not included in the models. The model was run with four chains of 2000 iterations and 1000 burn-in samples.

2.3.4. Handling time

The handling time model for angled Coho Salmon used a similar additive Bayesian regression framework with a gaussian-distributed response for fish handling time (in seconds). Model covariates included critical or non-critical hooking location, barbed or barbless hook, and single or multi-hook type covariates. The same regularized horseshoe prior as the C&R mortality models was applied for these covariates, and a random intercept parameter was applied for unique angling survey events. The model was run with four chains of 2000 iterations and 1000 burn-in samples.

3. Results

From June 1, 2017, to May 31, 2020, more than 7200 rod-hours resulted in angling 2700 salmon and steelhead trout, including non-target species. This resulted in 1446 unique tagged treatment Coho Salmon, Spring Chinook Salmon, and steelhead trout. Concurrent with angling surveys, 3791 fish were trapped at the CSS, tagged, and released into the lower Cowlitz River as control fish (Table 2). Most of these fish were Coho Salmon (n = 1096) and summer (n = 1832) and winter steelhead trout (n = 781). Eighty-two Spring Chinook Salmon were released as control fish. Returns of Spring Chinook Salmon 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 sources of recapture included spawning surveys (<1 %) and out-of-basin fish traps (<1 %). These recapture proportions were similar across species, with the exception of summer steelhead trout; of which 62.5 % were recaptured at the CSS and 35.2 % by anglers. Initial recaptures of treatment fish occurred between 1 and 97 days after capture (median = 18 days; Fig. 3).

3.1. Catch and release mortality

Full and regulatory models were fit for Coho and Chinook Salmon 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) since the control group was excluded from the analysis. For all models, the

Table 2
Annual totals of tagged control and treatment fish, percentage of recaptures, and returns to the Cowlitz Salmon Hatchery (CSH).

Species	Run Year	Control Release Group		Treatment Release Group		CSH Returns[a]
		Tagged	Recaptured [%]	Tagged	Recaptured [%]	
Coho	2017	316	239 [75.6]	246	180 [73.2]	39,037
	2018	390	277 [71.0]	319	243 [76.2]	12,959
	2019	390	313 [80.3]	369	288 [78.0]	21,337
	Total	1096	829 [75.6]	934	711 [76.1]	
Spring Chinook	2017	8	0 [0]	17	11 [64.7]	9393
	2018	74	56 [75.7]	131	73 [55.7]	2627
	2019	0	0	6	3 [50.0]	1269
	Total	82	56 [68.3]	154	87 [56.5]	
Summer Steelhead[b]	2017	295	148 [50.2]	21	16 [76.2]	1592
	2018	840	466 [55.5]	49	24 [49.0]	2296
	2019	697	338 [48.5]	49	12 [24.5]	1907
	2020	0	0	6	3 [50.0]	-
	Total	1832	952 [52.0]	125	52 [44.0]	
Winter Steelhead	2018	199	112 [56.3]	35	15 [42.9]	2942
	2019	390	205 [52.6]	37	14 [37.8]	1985
	2020	192	104 [54.2]	161	103 [64.0]	4807
	Total	781	421 [53.9]	233	132 [56.5]	

[a] CSH returns are up to date through July 24, 2020.
[b] Control summer steelhead totals includes fish released as part of Tacoma Power's recycling program.

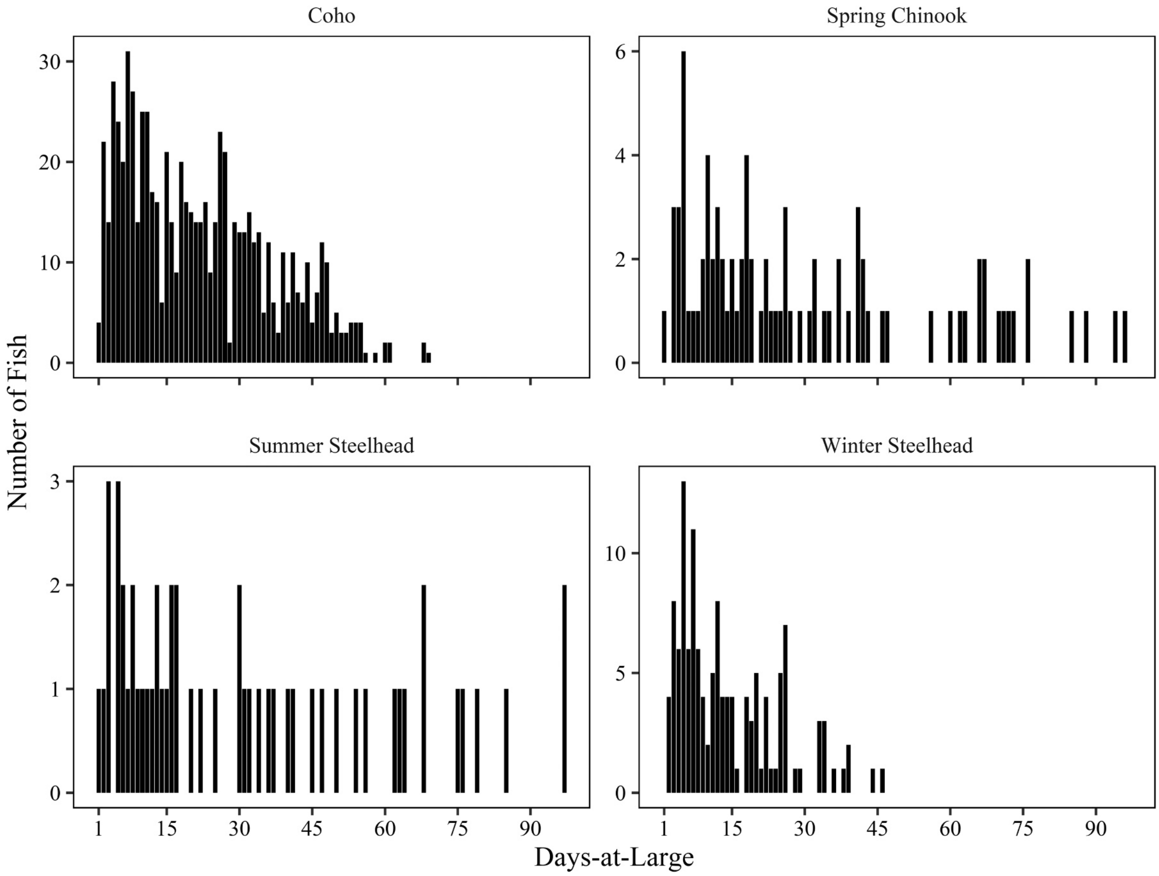

Fig. 3. Frequency of the number of days between capture and initial recapture of treatment fish by species and run type.

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 terms indicated some variation in recapture probability attributed to unique surveys and control releases. Spline terms in the Coho and Chinook models indicated variation in recapture probability based on the day and year of capture or release for control and treatment fish, respectively. The spline terms included in steelhead models indicated variation in recapture probability associated with day of year and year by run type, and river kilometer and run year by run type. Spline functions were consistent within species across models. Trace plots and β parameter Rhat values less than 1.05 indicated that all models converged appropriately.

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. Median relative C&R mortality predictions from the regulatory model were less than 1 % (median 95 % HDI −3.2 to 3.2 %), and did not indicate significant differences due to gear, barbs, or single and multiple hook types (Fig. 4).

Spring Chinook models provided minimal evidence for a treatment effect. Lower recovery probabilities were weakly associated with barbed hooks relative to non-barbed, non-critical hooking locations relative to critical hooking locations, and multiple hooks relative to single hooks (Table 4). The overall median predictions of relative mortality from the regulatory model ranged from 3.6 % (95 % HDI −0.6 to 30.1 %) to 10.2 % (95 % HDI −6.9 to 66 %) depending on gear type, barbed or barbless hook, and single or muti-hook type (Fig. 4). In all cases, the 95 % HDI for

Table 3
Coefficient estimates and associated highest density intervals (HDI) from the Coho Salmon catch and release mortality full model. Covariate coefficients are relative to non-angled control fish.

Covariate	Mean	Median	95% HDI, lower	95% HDI, upper	Probability of negative effect
Handling time	-0.0340	-0.0006	-0.2820	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	0.0000	-0.0628	0.0563	0.5088
Angling effect	-0.0017	0.0000	-0.0727	0.0666	0.5035
Multi-hook	-0.0033	0.0000	-0.0964	0.0679	0.5032
Single hook	0.0012	0.0000	-0.0651	0.0685	0.4958
Backtrolling with bait	0.0047	0.0000	-0.1088	0.1008	0.4948
Hook left in fish	-0.0019	0.0000	-0.1062	0.0893	0.4940
Barbless hook	0.0023	0.0000	-0.0681	0.0661	0.4852
Casting a lure	0.0005	0.0000	-0.0610	0.0694	0.4835
Drifting with bait	0.0064	0.0000	-0.1110	0.0881	0.4808
Casting a jig	0.0032	0.0001	-0.0554	0.0734	0.4690
Fork length	0.0046	0.0001	-0.0443	0.0758	0.4650
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

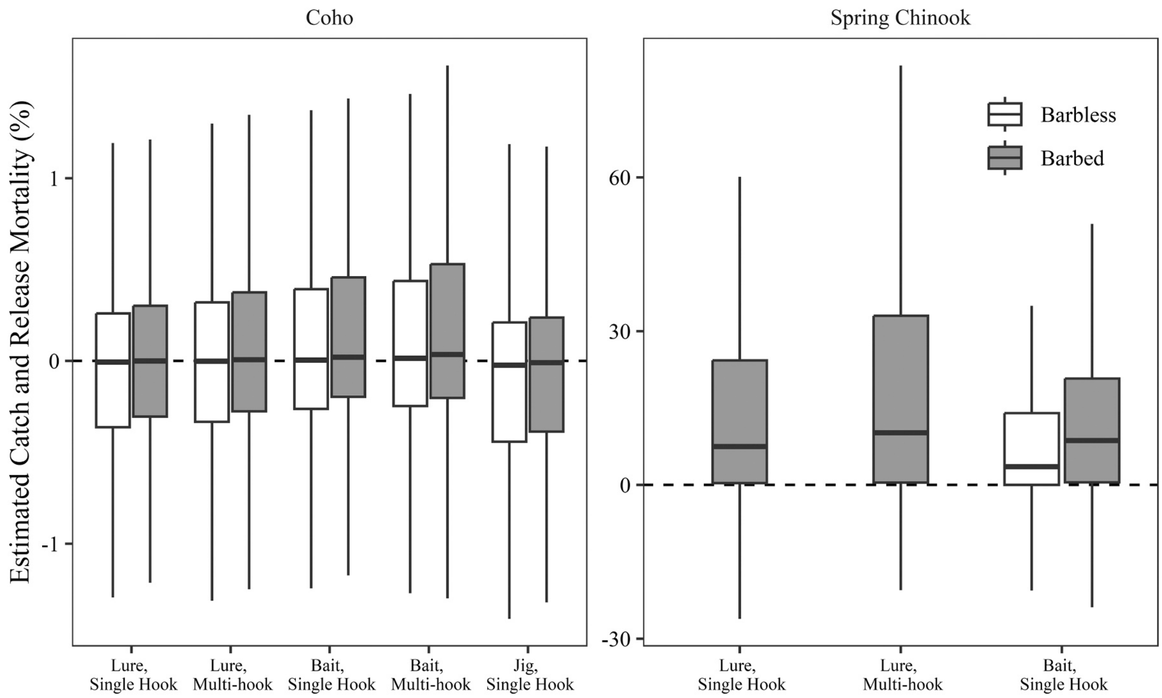

Fig. 4. Estimated catch and release mortality for Coho Salmon and Spring Chinook Salmon, given the combinations of gear, single or multi-hook types, and barbed or barbless hooks.

Table 4
Coefficient estimates and associated highest density intervals (HDI) from the Spring Chinook Salmon catch and release mortality full model. 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	0.5930
Multi-hook	-0.1092	-0.0030	-0.9867	0.2876	0.5918
Hook removed	-0.0385	-0.0016	-0.4630	0.2317	0.5750
Non-critical hook location	-0.0504	-0.0019	-0.508	0.1907	0.5738
Bobber with bait	-0.0343	-0.0010	-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	0.5510
Temperature	-0.0263	-0.0008	-0.3822	0.2360	0.5508
Critical hook location	-0.0188	-0.0004	-0.3993	0.2193	0.5295
Barbless hook	-0.0047	0.0000	-0.2763	0.2390	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	0.0280	0.0011	-0.1623	0.3320	0.4472

estimates of relative mortality included zero.

Steelhead models did not provide any evidence for variation in recapture rates among angled fish. In the full model, posterior distributions of covariate effects all straddled zero. Similarly, recapture probabilities predicted from the regulatory model did not display significant variation for gear, barb, and single or multiple hook type combinations (Fig. 5).

3.1.1. *Landing probability*

During angling surveys, 2509 Coho Salmon, Spring Chinook Salmon, and steelhead trout were hooked and 2039 were successfully landed. The landing rate models indicated that barbed hooks were likely associated with increased landing probability for all species when compared to barbless hooks, however, the 95 % HDIs overlapped in all cases (Fig. 6). Coefficient estimates for number of hooks were at or near zero and subsequently removed from the models. For Coho Salmon, barbless and barbed hooks were estimated to result in landing probabilities of 0.81 (95 % HDI 0.78 – 0.85) and 0.87 (95 % HDI 0.84 – 0.89), respectively. Barbed hooks were also associated with an increase in landing probability for Spring Chinook Salmon compared to barbless hooks, from 0.75 (95 % HDI 0.65 – 0.86) to 0.89 (95 % HDI 0.82 – 0.94). Similarly, the landing probability for steelhead was lower when barbless hooks were used compared to barbed hooks, estimated at 0.63 (95 % HDI 0.56 – 0.72) and 0.74 (95 % HDI 0.70 – 0.79), respectively.

3.1.2. *Hook location*

The hook location model for Coho Salmon revealed differences in the probability of hooking Coho in a critical location for some angling method and gear type combinations (Fig. 7). The median probability of critical hook locations while casting with jigs and lures were 0.02 (95 % HDI 0.01 – 0.03) and 0.05 (95 % HDI 0.03 – 0.08), respectively, while using a bobber with bait resulted in a critical hook probability of 0.19 (95 % HDI 0.12 – 0.28). The small sample sizes for angling method and gear type combinations drifting ($n = 11$) and backtrolling ($n = 2$) with bait resulted in limited capacity for inference.

3.1.3. *Handling time*

The handling time model for Coho Salmon indicated that barbed hooks were the most likely covariate to influence fish handling duration. Barbed hooks were associated with a three second median increase in handling time (mean = 95 s; 95 % HDI −0.58 to 8.52) compared with barbless hooks, and a 0.91 probability that the effect was positive. Critical hook location and multi-hooks were predicted to marginally increase handling time, however the 95% HDIs straddled zero (critical hook location −2 to 7.14; multi-hook −2.36 to 6.26) and the probabilities of positive effect were 0.69 and 0.67, respectively.

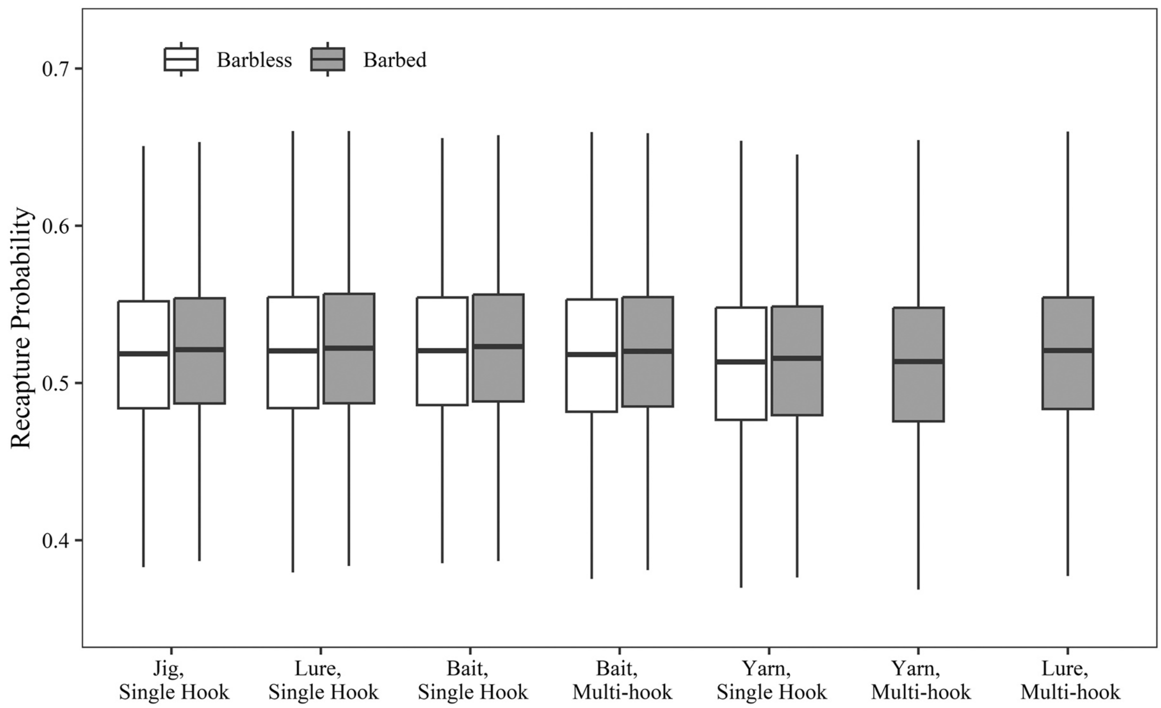

Fig. 5. Estimated variation in recapture probability for angled steelhead trout, given the combinations of gear, single or multi-hook types, and barbed or barbless hooks.

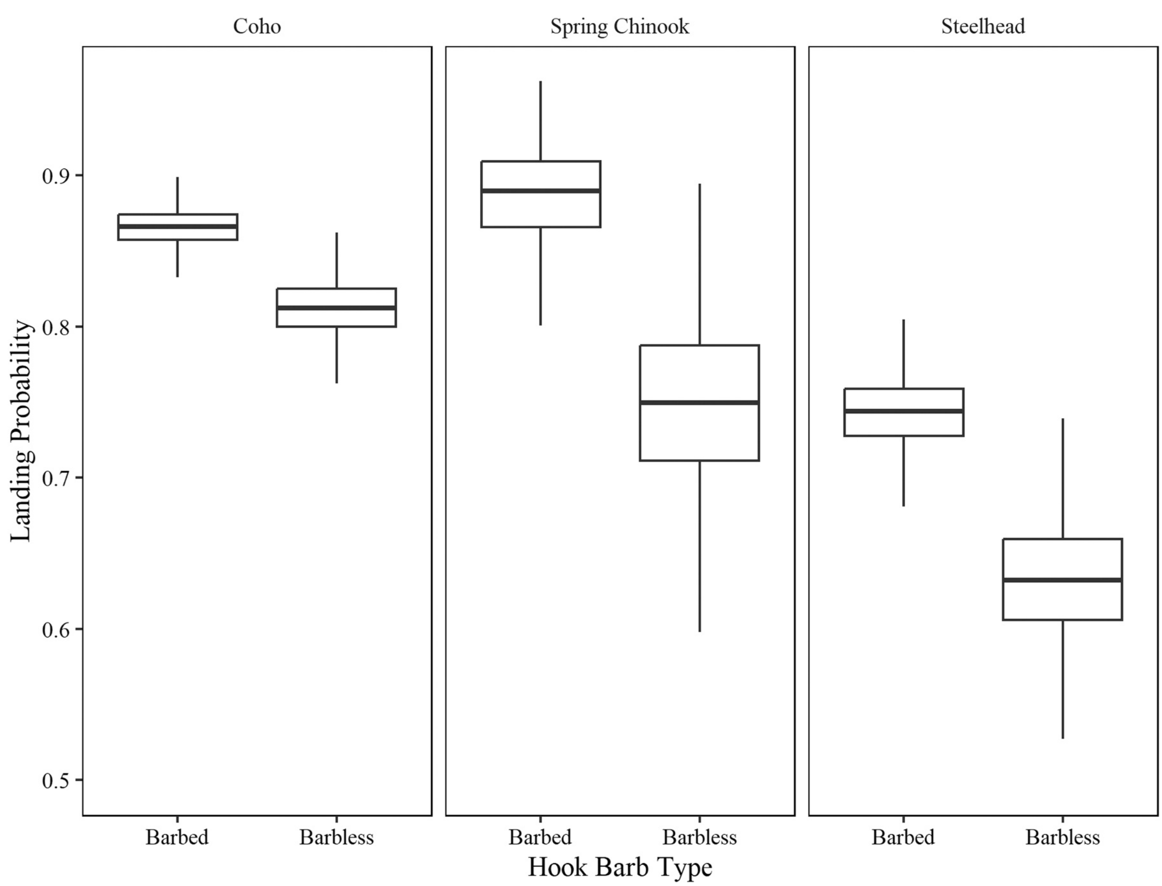

Fig. 6. Landing probability for Coho Salmon, Spring Chinook Salmon, and steelhead trout, given barbed and barbless hook types.

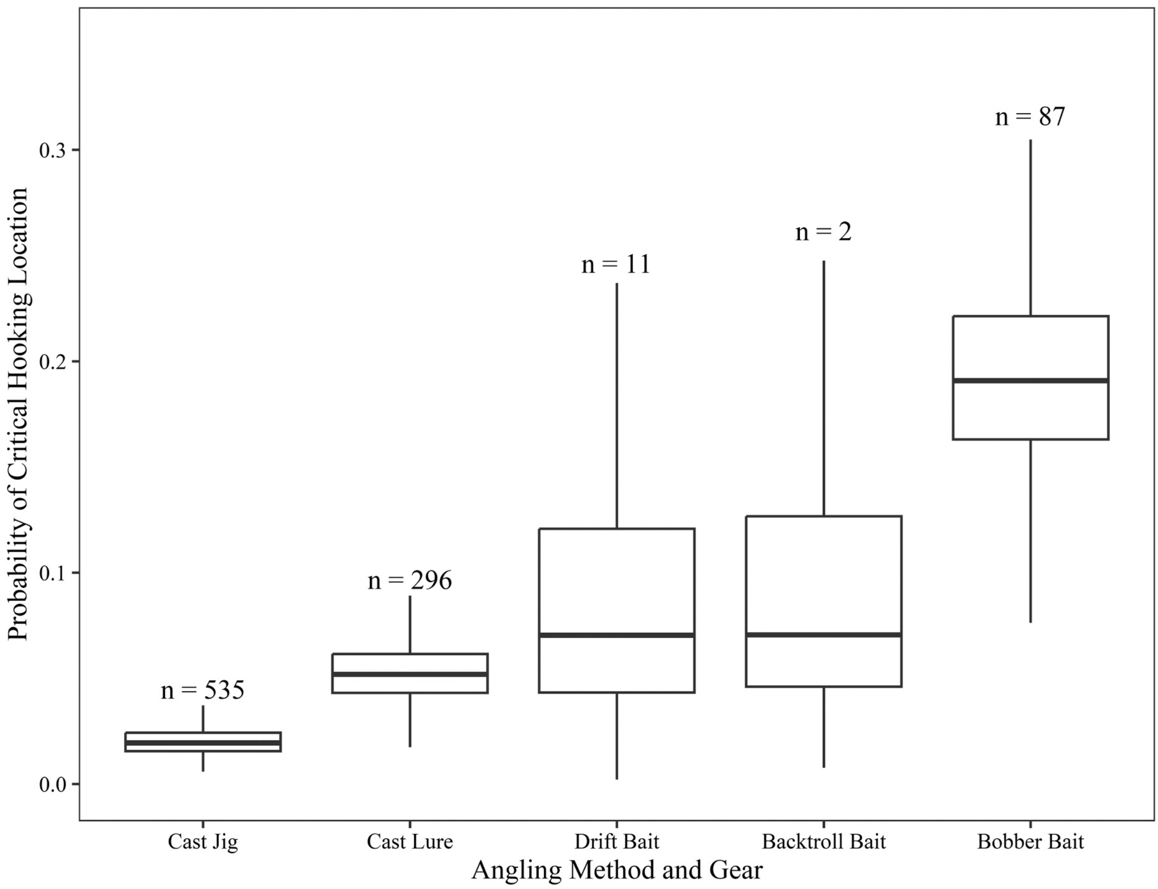

Fig. 7. Critical hook probability for Coho Salmon by combinations of angling method and gear type. n = sample sizes for each angling method and gear type combination.

4. Discussion

C&R survival studies have been conducted on recreational salmon and steelhead 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. 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 on multiple anadromous salmonid species. Our dataset also proved useful for examining effects of terminal gear type and fishing methods, fight time, handling time, and hook location.

Coho Salmon survival was high after C&R with no clear evidence for differences in recapture rates between control and treatment fish. Stuby (2002) reported 15 % C&R mortality for Coho Salmon caught on lures, but our results suggest 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 we angled few Coho Salmon with bait, which was less effective in the fishery. However, we did find indirect evidence that terminal tackle may influence Coho Salmon survival. Specifically, use of bait increased the probability of hooking fish in critical locations. Vincent-Lang et al. (1993) estimated 11.7 % C&R mortality for Coho Salmon angled using bait and found hook location significantly affected survival rates.

Unlike our results for Coho Salmon, we found evidence for C&R effects on Spring Chinook Salmon, which experienced 3.6–10.2 % mortality relative to non-angled control fish, depending on terminal tackle. These results are similar to those of previous studies that estimated Chinook Salmon C&R mortality between 7.6 % and 12.2 % (Bendock and Alexandersdottir, 1993; Fritts et al., 2016; Lindsay et al., 2004), but differ from the 0.9% mortality reported by Cowen et al. (2007). It is reasonable to assume that higher rates of mortality for Spring Chinook in our study relative to Coho Salmon could have been attributed to preferential use of bait while targeting Chinook in the fishery. Despite Spring Chinook being most-frequently angled using bait, median survival rates were similar to Chinook angled with lures.

Terminal tackle are commonly regulated to reduce impacts of C&R. Therefore, we tested the efficacy of purported conservation measures, such as restricting use of barbed hooks. Lower recapture probabilities were weakly associated with barbed hooks relative to barbless hooks. These 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 reported barbless hooks result in higher C&R survival of Coho Salmon (Gjernes et al., 1993) and resident trout (Taylor and White, 1992). We found 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, there were substantial differences in landing probabilities between the two hook types. Similar to Bloom (2013), DuBois and Dubielzig (2004), and Meka (2004), we found that angling with barbless hooks resulted in lower landing probabilities. This was an important finding that should be useful to managers when assessing trade-offs between conservation and harvest opportunity within recreational fisheries. For example, restricting anglers to use of barbless hooks in hatchery-supplemented fisheries may substantially impact harvest rates without providing a significant conservation benefit. Conversely, it may be prudent to restrict barbed hooks in C&R fisheries where fish retention is not allowed, and the intent is to minimize impacts on natural-origin fish.

Surprisingly, we did not find that increased surface water temperature at capture negatively affected salmon and steelhead C&R survival as was reported by Bartholomew and Bohnsack (2005) and Bentley and Rawding (2016). We suspect this was because temperatures in the Cowlitz River remain within the physiological optima for salmonids. Reservoirs in the Basin moderate river temperature conditions such that peak summer temperatures rarely exceed 16 degrees Celsius and winter temperatures remain above 10 degrees Celsius. We expect that temperature effects are stronger in rivers where water temperatures approach and surpass critical stress thresholds for salmonids–approximately 18 degrees Celsius or higher.

Some researchers have reported relatively high C&R mortality for resident salmonids (Huhn and Arlinghaus, 2011). This may be because resident fish are generally smaller than anadromous fish, and smaller salmonids can be more vulnerable to mortality due to serious injury from handling and hook removal (Meka, 2004; Schisler and Bergersen, 1996). Furthermore, small fish need to recover and continue actively feeding, whereas adult salmon and steelhead undergo prolonged fasting prior to spawning (Penney and Moffitt, 2014). Given differences in life-history and size of resident and anadromous salmonids, it is reasonable to expect that specific terminal tackle types, such as barbed hooks, may have greater impacts on smaller salmonids relative to what we observed for adult anadromous salmonids.

Our study addressed a key shortcoming of previous research by documenting recapture rates of non-angled fish to serve as controls. However, these control fish were imperfect surrogates for other non-angled fish in the population. Impacts of electro-immobilization, handling, and transport of control fish could have positively biased survival estimates for angled fish. We believe these impacts were minimal because CSS operators routinely assesses mortality for hatchery broodstock, and impacts of electro-immobilization at the CSS were found to be negligible (Nguyen et al., 2018). Future C&R survival studies should consider marking outmigrating juvenile fish with Passive Integrated Transponder tags so they can be detected without capture and handling when they reenter the study area as adults. This would allow for survival estimation methods similar to those described by Skalski et al. (2010).

Generally, effects of C&R, angling methods, and terminal tackle were small, with relatively high levels of uncertainty. As such, implementing angling restrictions to minimize impacts of C&R may be less effective than other conservation actions. Previous research has shown that when C&R mortality is low, recreational angling impacts are minimal, even during years of low abundance (McCormick et al., 2021). Correspondingly, liberalizing gear regulations should not be expected to appreciably impact salmon and steelhead populations. Anadromous salmonids are known to respond to density such that small changes in C&R survival will not likely result in changes in population-level abundance or long-term persistence relative to other factors, such as spawning and rearing habitat conditions, predation, migration impediments, and ocean conditions (Nehlsen et al., 1991).

We designed our study to address mortality as the primary experimental endpoint. However, sublethal impacts of angling on anadromous salmon and steelhead is also a management concern. 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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CRediT authorship contribution statement

Ian I. Courter: Funding acquisition, Conceptualization, Methodology, Investigation, Project administration, Writing – original draft, Writing – review and editing. **Thomas Buehrens:** Methodology, Formal analysis, Writing – original draft, Funding acquisition. **Mark Roes:** Formal analysis, Visualization, Writing – original draft, Visualization, Investigation. **Tara E. Blackman:** Data curation, Methodology, Visualization, Writing – original draft, Writing – review and editing. **Benjamin Briscoe:** Investigation. **Sean Gibbs:** Investigation, Writing – original draft, Writing – review and 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

Data will be made available on request.

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