


# Systematic Literature Review of Pacific Salmon Hatchery Release Strategies in Canada and the United States

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# EXECUTIVE SUMMARY


This review was undertaken by the Pacific Salmon Foundation to collate and summarize the available literature on Pacific salmon hatchery rearing and release strategies tested and used throughout British Columbia and the western United States. Specifically, we included studies on the effects of key release strategies on survival, catch, age at return, sex ratios, and size at return published since 1970. The following release variables were considered: size at release, time of release, rearing, release type, and life stage.

The literature search returned a total of 1,123 unique references. Of these, 76 met the screening criteria, covering a broad range of release strategies from California along the coast to Alaska. Research on hatchery strategies has steadily increased over the past 50 years, with significant contributions from federal, state, provincial, and academic scientists. The majority of this work has focused on systems in Washington and Oregon, although BC was a key player in much of the early research on release strategies. Chinook have been the most commonly studied species, with a dramatic increase in research on this species in the past ten years. The most well studied strategy has been the size of subyearling and yearling smolts at release, followed by the time of release and rearing conditions.

The following summarizes some of the key findings in the literature reviewed.

- Hatchery rearing and release strategies have had demonstrable, though variable effects on survival and biological traits.
- Studies revealed increased or no change in survival of smolts released at a larger size for all species. There were no reports of larger sized smolts having lower survival for both Chinook and steelhead, and only one report of this in Coho. However, releases of larger smolts decreased the age at return in 47% of studies on Chinook and 92% of studies on Coho.
- Chinook and Coho responded differently to the timing of release. Later Coho releases had higher survivals in 46% of the studies, while later Chinook releases had lower survivals in 43% of the studies. Furthermore, late released Coho had higher catch in fisheries, returned at older ages, but as smaller adults, while mixed or no relationships were reported for Chinook catch, return age and size at return.
- The most commonly reported (43%) relationship between rearing density and survival was negative.
- Of the four studies on semi-natural rearing, one in BC reported increased returns from the semi-natural treatment, while those in Washington reported mixed, negative, or no effects.
- Acclimation prior to release has seen mixed results across species, however seapens have had consistently positive outcomes for survival in Alaska. There, seapen-reared Coho were also reported to return as larger adults, however there was no reported effect on Chinook size at return.
- Releasing smolts volitionally, rather than forcing them out has, yielded similar or lower returns. In addition, the one study on Coho observed a higher proportion of jacks returning from volitional releases, however no effects were observed on the return age of steelhead.
- The release of older life stages (i.e. smolts versus fry, or yearling smolts versus subyearling smolts) consistently resulted in higher survival.

The development of optimal release strategies requires a thorough understanding of the complex relationships between genetics, hatchery rearing and release practices, and environmental conditions. The intention of this review is to deepen that understanding, but also to highlight gaps in our knowledge and areas for future research. Much of the literature for BC and Alaska is more than 30 years old and likely outdated. Studies on release strategies for Chinook beyond Washington and Oregon and for steelhead beyond Oregon are lacking. Understudied strategies, such as rearing water and container type, seapens, and semi-natural rearing are areas for future research. In addition, while most studies measure the response of survival to changing strategies, more can be learned about other outcomes, such as the response of fisheries, sex ratios, and the size at return. In addition, half of the studies had only 1-3 years of data. Given the amount of environmental variability driving trends in survival, studies should extend over longer time periods or be repeated over time.

Photo by: Mitch Miller

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# INTRODUCTION

Pacific salmon are at the heart of ecosystems, communities, economies, and cultures along the Northern Pacific rim. However, over time, societal development has had negative effects on wild salmon and their habitats. Natural resource development such as logging and mining has resulted in significant habitat degradation, dams have blocked upriver migrations, and periods of voracious commercial fishing have led to overharvesting (Lichatowich 1999). The early hatcheries were established to mitigate the negative effects of development and maintain salmon harvest levels. The idea was that producing and rearing salmon in a controlled environment could increase early life survival and thus yield higher overall survival rates than seen in the wild. By the 1960s, our understanding of the salmon life cycle and salmon rearing practices had improved, and a rapid expansion in hatcheries and hatchery production occurred over the next several decades.

Concurrently, the productivity of many salmon populations throughout the northeast Pacific declined in the late 1980s (Peterman et al. 2012, Riddell et al. 2013, Zimmerman et al. 2015, Kendall et al. 2017) and questions began to arise on the environmental impacts of hatcheries. As the health of salmon populations changed, so too did the goals behind salmon enhancement. The focus shifted from mitigation and production for harvest towards conservation and the balance of enhancement, habitat, and harvest. Today, guidelines are in place to minimize the impacts of hatcheries on other fish stocks, reduce their ecological impacts on natural systems, and maintain genetic diversity while optimizing survival and maintaining opportunities for harvest.

The strategies hatcheries employ for rearing and releasing fish are critical to meeting their goals and objectives. These strategies have evolved over time to improve hatchery efficiency and increase post-release survival. Rearing strategies include decisions made about the hatchery environment, such as water source, rearing containers and density. Release strategies refer to elements such as the size at release, timing of release, nature of release (i.e. forced out all at once or allowed to leave the hatchery volitionally), and the use of acclimation facilities prior to release.

Hatchery managers therefore face the challenge of proactively developing rearing and release strategies that maximize survival pre- and post-release given localized limitations at the facility or in the environment, while meeting management objectives and minimizing risk. For instance, releasing fish later than their wild counterparts could reduce instream competition and yield higher returns (Quinn et al. 2005). However, longer rearing may increase operational costs, produce smaller-sized adult returns, and create a temporal mismatch between the time of ocean entry and peak prey abundance (Satterthwaite et al. 2014). These benefits and costs will vary between stocks and facilities, therefore each facility must carefully consider the best rearing and release strategies suited to meeting their objectives.

Hatchery managers and scientists have been experimenting with rearing and release strategies since hatcheries began. These experiments have provided valuable insight into the drivers of survival, harvest rates, and conditions at return of enhanced salmon populations and have shaped hatchery practices used along the Pacific coast today. It is important that we learn from previous research to make the most informed decisions on the use of hatchery rearing and release strategies to achieve management objectives. A technical report from the Oregon Department of Fish and Wildlife reviewed Coho release strategies in British Columbia (BC), Washington, and Oregon between 1933 and 1978, providing a detailed history and evolution of hatchery practices that have led to many of the strategies used today (Johnson 1982). While the report points to optimal release periods and sizes for Coho, it also highlights interannual variability and the need to evaluate the effects of release strategies over time and under various environmental regimes. It also called for greater tagging of enhanced fish to be able to effectively evaluate the success of release strategies and laid the foundation for future similar assessments. Since then, other reviews have been published in the grey literature on specific species or strategies (e.g. Maynard et al. 2004, Poirier & Olson 2017), however, there has been no comprehensive synthesis of the literature on rearing and release strategies to date. Therefore, a systematic literature review was conducted to summarize the existing state of knowledge. In synthesizing the outcomes of all available research, we identified recurring outcomes from specific strategies, identified regional and temporal trends by species, and highlight the remaining gaps in our knowledge to guide future research.

# METHODS

## Literature Search

An initial systematic literature search was conducted in December 2019 of the peer-reviewed and grey literature published between 1970 and 2020 to synthesize existing knowledge on the use and effects of hatchery release strategies on Pacific salmon in the northeast Pacific. While the original intention was to provide a review for BC exclusively, a preliminary search suggested that data were limited for this region. Therefore, we expanded to include literature from enhancement facilities in the United States. The search keywords were revised in December 2020 and the literature search updated in January 2021. The following is a description of the revised methods and numbers and sources of references from both searches combined (see Figures A1-A2 in Appendix for detailed description of each search).

A keyword search was conducted using two commercial academic search engines, Web of Science Core Collection (WoS) and Aquatic Sciences and Fisheries Abstracts (ASFA) to capture peer-reviewed literature. The Fisheries and Oceans Canada (DFO) Library, and the Google Scholar search engine were used to find additional grey literature. Google Scholar's search algorithm is unknown, making it difficult to optimize a search and often finding thousands of sources that may or may not be related to your search. Therefore, the first 200 records were taken, and up to an additional 100 references were taken from each of a Google search of 'fws.gov' sites, and a Google search of 'noaa.gov' sites. The following combinations were used:

1. keywords for the species of interest (Chinook OR "*Oncorhynchus tshawytscha*" OR Coho OR "*Oncorhynchus kisutch*" OR Sockeye OR "*Oncorhynchus nerka*" OR "Pink salmon" OR "*Oncorhynchus gorbuscha*" OR "Chum salmon" OR "*Oncorhynchus keta*" OR steelhead OR "*Oncorhynchus mykiss*");
2. the keyword hatcher*;
3. keywords to focus the search on the northeast Pacific ("British Columbia" OR "Salish Sea" OR BC OR Washington OR Oregon OR Columbia OR California OR Alaska OR Idaho OR Snake);
4. the keyword releas*;
5. keywords to capture studies with adult return data (return* OR catch* OR harvest OR escapement OR surviv*);

wherein the asterisk is commonly used to allow search engines to find any words beginning with that term (e.g. hatcher* can yield results for hatchery and hatcheries).

All references found from both searches were saved and duplicates within and between searches were removed. The titles and abstracts of the remaining references were screened for eligibility. Only research at American or Canadian facilities that examined the effects of key release strategies on survival, catch, age at recovery, adult size, and sex ratios of Pacific salmon species in the northeast Pacific were included. The key release strategies included time of release, size at release, life stage, rearing practices (container type, density, rearing water, semi-natural versus conventional), and release types (forced versus volitional, acclimated versus direct). Release strategies such as transportation, varying feeding regimes, or release during certain environmental time frames (e.g. periods of high/low river discharge rates, lunar cycles) were not considered in this review. Furthermore, only references with statistical analyses, rather than descriptive summaries, were included. For those references passing the first found of screening, the full texts were read for eligibility. Data were then extracted from all eligible references and backwards reference screening was conducted by browsing their references for any additional literature that may have been missed by our search. One additional technical report was provided by a reviewer prior to the final submission of this report.


## Data Extraction

To assess trends in the literature, several parameters were extracted from each reference. The key parameters extracted for analyses were:

1. Publication date;
2. First author affiliation;
3. Country, region, and system in which the fish were released;
4. Species and life stage released;
5. Brood years of the study;
6. Release strategy type (life stage, rearing, release, size, time);
7. Treatment (e.g. 'increase' for size and time experiments, or descriptor of categorical treatments);
8. Response variable (survival, catch, age, size, % males);
9. Nature of the response (positive/negative, quadratic, higher/lower, mixed, none);
10. Numbers released per treatment and total release numbers;

The full dataset for this review can be found on the Strait of Georgia Data Centre.

The release strategies involving the time of or size at release were treated as continuous variables that either increased or decreased relative to the 'normal' treatment group. All other release strategies were treated as categorical variables with discrete treatments (e.g. acclimated or direct, semi-natural or conventional, etc.). There were a number of different ways in which 'survival' was described in the literature, including smolt-to-adult survival (SAS), smolt-to-adult return (SAR), and recruitment. For the sake of this review, all have been categorized as 'survival'. Throughout the review, the effects of hatchery rearing and release strategies on jacking rates (the proportion of precocious males in returns) were often grouped with those looking more broadly at trends in age at return to create a single response for 'age at return'.

It should be noted that some of the references contain data for multiple unique studies. Throughout this review, we use the terms 'reference' and 'study' to refer to the publication and the individual experiments, respectively.

# RESULTS

## Research Trends

A total of 1,123 unique references were found as a result of our search. Of these, a total of 63 met our eligibility criteria once we had completed the screening process (Table 1). The other references were excluded primarily because they were not hatchery related or did not report on any release strategies. An additional twelve eligible references were identified through backwards reference screening and one was provided by a reviewer, resulting in a total of 76 references. Results of the full screening process can be found in the Appendix (Figures A1-A2).

Of the 76 references found, only 12 (16%) were from studies conducted in British Columbia (BC) with the other 64 from studies in the United States (US) (84%) (Table 2; Figure 1). One region-wide study was found for the North East Pacific (NE Pacific) (Hobday & Boehlert 2001). Data for these studies came from over 70 enhancement facilities across both countries. While most (90%) references were from peer-reviewed journals, eight were technical reports (six from government, one academic, and one consultancy). Publications ranged in their authorship, with the majority coming from members of the National Oceanic and Atmospheric Administration (NOAA), followed by academics and members of the Washington Department of Fish and Wildlife (WDFW), and the Oregon Department of Fish and Wildlife (ODFW)(Table 1; Figure 2).

Chinook (*Oncorhynchus tshawytscha*) and Coho (*Oncorhynchus kisutch*) salmon were the most frequently studied species, followed by steelhead trout, with very few studies on Pink (*Oncorhynchus gorbuscha*) or Sockeye salmon (*Oncorhynchus nerka*) and no studies on Chum salmon (*Oncorhynchus keta*) (Tables 1 and 3). In each US state, Chinook were the focal species of 50% or more of the research, whereas in BC, Coho were the subject of 67% of the studies. Meanwhile, most of the research on steelhead was from Oregon (58%).

There has been a great deal of variability in the number and nature of studies done on hatchery strategies over the last 50 years. The oldest publication was from 1976 and the most recent from 2020, with a notable increase in the number of publications in the last decade (Figure 2A). The actual brood years included in these studies span 1950 to 2012. The research bodies contributing to the literature has also varied over time, with DFO and NOAA scientist leading much of the early research on release strategies and NOAA, ODFW, WDFW, and university scientists leading in recent years (Figure 2B). Most of the research from BC was published in the 1980s and 1990s, with four references found from the last 20 years. Literature from Alaska was also more abundant in the 1980s while literature in the last two decades has come largely from Washington and Oregon (Figure 2C). The species of interest also varied over time (Figure 2D). Coho were the focus of the early studies in the 1970s and 1980s, while steelhead trout began to receive more attention in the 1990s. Chinook have become the most commonly studied species in the past 10 years.

We examined Chinook and Coho survival trends over time (from Riddell et al. 2013 and Zimmerman et al. 2015) to determine if there was any bias in the literature towards reporting from periods of high or low survival. Several stocks exhibited sharp declines in the late 1970s and 1980s, followed by an extended period of low survival rates (e.g. south-east Alaskan Chinook, Strait of Georgia Chinook and Coho, southern Puget Sound Chinook and Coho), while others have fluctuated over time (e.g. WCVI Chinook, middle and upper Columbia Chinook, and lower Columbia Coho) (Figures 3 and 4). For Chinook, there have been more publications from periods of low survival than from periods of high survival, while the inverse is true for Coho. However, the distribution of studies across high and low survival years varied by region.

Size at release and time of release have been the two most commonly studied release strategies, however, studies on rearing practices and release types have increased in the last 20 years (Tables 2-3; Figure 5). Survival has consistently been the most common response variable studied, followed by age at return and size at return (Tables 2-3; Figure 5). The studies ranged in their level of complexity. All studies except two examined a single species of salmon. While most studies were also based at a single enhancement facility, about a third looked at salmon from multiple facilities. The number of brood years was heavily right-skewed, with a median of three years but a range of 1-50 years. Only 45% of the literature ran experiments for more than three brood years, while only 9% of the studies spanned more than 10 brood years.

## Synthesis of Effects of Rearing and Release Strategies

### Size at release

The size of hatchery salmon at release has been the primary release strategy studied in the literature reviewed (n = 39; Tables 1-3). It is believed that size-specific growth and mortality rates in the early marine period determine survival, with larger fish exhibiting faster growth, and thus higher survival (Beamish et al. 2004, Duffy & Beauchamp 2011). In the literature reviewed, increasing the size of hatchery fish released has either yielded higher survival rates, or has had no effect (Tables 4-6; Figures 6-7). In an analysis of 26 years of Coho releases across the west coast of North American, the effects of size at release varied by region (Hobday & Boehlert 2001). In northern BC and Alaska, increased size at release resulted in increased survival, however in the Strait of Georgia and south along the coast of Washington and Oregon, survival rates decreased as weights increased to 30 g, and then increased for those released larger than 30 g. Meanwhile, in an evaluation of Coho release strategies into the Strait of Georgia from five facilities over 28 years, heavier smolts had significantly higher survival rates than lighter smolts at four of the five facilities (Irvine et al. 2013). One of the facilities in the analyses, Chilliwack River, showed a temporal trend in this relationship, with increased size of release having a greater effect on survival in recent years. However, in another study of Coho salmon released into Puget Sound from 1969 to 1998, size did not explain the variation in survival over the time series (Quinn et al. 2005).

The effects of size at release reported from individual experiments were variable, even for the same species released in the same system in the same decade (Tables 4-6). For example, size at release experiments conducted on brood years 2000-2009 of Chinook salmon released into the Columbia and its tributaries reported both an increase in survival when larger smolts were released (Zabel & Williams 2002, Tipping 2011, Passolt & Anderson 2013, Beckman et al. 2017), and no difference in survival between size groups (Table 4; Zaugg 1989, Beckman et al. 1999, Claiborne et al. 2011, Tipping 2011, Feldhaus et al. 2016, Harstad et al. 2018). However, other regions with single studies on size at release, such as California's Central Valley or the Unuk River, Alaska, have also reported higher survivals of smolts released at larger sizes (Martin & Wertheimer 1989, Sabal et al. 2016). Releasing Chinook at larger sizes has not been found to have a negative effect on survival in any of the literature reviewed. The only report of a larger size at release resulting in lower survival came from a 3-year study on Coho salmon across three facilities in Washington (Tipping 2008b). One of the three facilities, George Adams Salmon Hatchery on the Skokomish River, reported significantly lower survivals of the larger yearling releases. Within each year, the larger size at release at George Adams was one of the largest sizes across all three facilities, therefore there may be some size threshold beyond which increasing size no longer yields a survival advantage. For steelhead, larger sizes at release have consistently yielded higher survival rates (Table 6; Slaney et al. 1993, Tipping 1997, Clarke et al. 2014, Thompson et al. 2018).

Many of the earliest studies of release strategies focused on the effects of size at release, the results of which were then often used to guide standard release practices moving forward. For instance, in BC, some of the early and often cited studies on the effects of size and time at release are those done on Vancouver Island, BC, during the 1970s and 1980s. Experiments at Rosewall Creek involved grading juveniles into three size groups (small, medium, large) and releasing all three sizes on four dates (April, May, June, and July) in 1973 (Bilton et al. 1982). At the time, the aim was to better understand the influence of time and size at release on survival, growth, and age at maturity, with the intention of improving the biological effectiveness of hatcheries. Earlier releases of small fish and later releases of large fish both had higher survivals. As a result, similar experiments were conducted on Coho and Chinook at Quinsam River Hatchery on the east coast of Vancouver Island in two consecutive years to determine if the effects of size and time could be expanded across other facilities and years. For Chinook, survival was highest for larger (6-10 g) juveniles in May (Morley et al. 1996). For Coho, survival was highest for releases of 20 g yearlings between June 4 and June 6, although the timing of releases was more important than the size (Bilton et al. 1984, Morley et al. 1988). To this day, many of the standard release strategies employed by hatcheries around the Strait of Georgia are based on these early experiments. However, these experiments are outdated, and optimal sizes at releases are believed to be more of a "moving target" given significant random interannual variation in survival rates (Irvine et al. 2013).

Limited information was available on the effects of size at release on catch (Tables 4-6; Figure 6). For BC, information on this relationship comes from research conducted in the 1970s and 1980s. In the Strait of Georgia, increasing the size at release of Coho generally had no effect on catch (Morley et al. 1988), although quadratic responses were observed in two release groups (Bilton et al. 1984). No effects were reported for Chinook releases in this area (Morley et al. 1996). On the east coast of Vancouver Island, an increase in the size of Chinook at release resulted in an increase in captures in BC waters (relative to the Alaskan fishery) (Green & Macdonald 1987). However, the relationship was slight and most of the variation in capture rates was explained by the effect of brood year. In Washington, modelling of Coho survival to recruitment in Puget Sound suggested that Coho catch would increase up to a release weight of 70 g, and then decrease beyond that size (Mathews & Buckley 1976). In Oregon, releasing larger Chinook yearlings resulted in a decrease in catch, with higher catches of small releases (Feldhaus et al. 2016). Meanwhile, an analysis of 28 years of Chinook releases of Central Valley Chinook reported a positive relationship, with higher ocean recovery rates of heavier smolts (Satterthwaite et al. 2014).

There has been significant evidence of a decrease in return age associated with increased weights at release, particularly for Coho (Tables 4-6; Figures 6 and 8). For Chinook, half of the studies on size at release reported a decrease in return ages in response to an increase in the size at release (Martin & Wertheimer 1989, Ewing & Ewing 2002, Claiborne et al. 2011, Harstad et al. 2014, 2018). In the Strait of Georgia, BC, no effect of release size was observed on the return age of Chinook releases (Morley et al. 1996). In Washington, an analysis of 50 years of Chinook release data from the University of Washington facility in Puget Sound found no effect of size at release on the proportion of jacks in the returns (Vøllestad et al. 2004). However, through the use of PIT tags on the Columbia River, a higher proportion of Chinook jacks were observed returning from the larger size at release groups (Harstad et al. 2018). Specifically, a 1% increase in size at release increased the odds of returning at age 2 by 6-9%. In addition, minijack (fish that return after only a few months in the marine environment) rates were found to increase from the release of larger fish throughout the Columbia River system (Harstad et al. 2014). In the Imnaha River, Oregon, ten years of Chinook releases found that smaller smolts yielded significantly more age-5 females, however there was no effect on the age of return of males (Feldhaus et al. 2016). No effects were observed in smolt releases into Hood River, Oregon, or Chickamin River, Alaska (Hard et al. 1985, Spangenberg et al. 2014). For almost all reports of Coho in BC, Washington, and Oregon, jacking rates were higher for larger releases (Hager & Noble 1976, Bilton et al. 1982, 1984, Morley et al. 1988, Fagerlund et al. 1989, Hopley et al. 1993, Vøllestad et al. 2004, Koseki & Fleming 2006, Tipping 2008b). The only exception was in Coho released from Marblemount Fish Hatchery into Puget Sound, where release size had no effect on the age at return (Tipping 2008b).

Size at release had no effect on the sex ratios of returning adults in 62% of studies (Tables 4-6; Figure 6). For Chinook, the only study wherein size at release was related to sex ratios of adult returns found a larger size at release to yield a higher return of males at a facility in Puget Sound (Tipping 2011). This is likely confounded by the higher jacking rate associated with the larger size at release. For Coho, trials in the Strait of Georgia yielded mixed results (Bilton et al. 1984, Morley et al. 1988, Fagerlund et al. 1989). Releases of larger fish into the Toutle River, Washington, also resulted in a higher proportion of male returns (Tipping 2008b), but again, this may be attributed to the higher jacking rates of the larger-sized releases.

Similar to the effects on sex ratios, 50% of studies on the effects of release size on adult size at maturity reported no effect (Tables 4-6; Figure 6). For Chinook trials in the Strait of Georgia and on the Columbia River system, size at release had no effect on adult size at return (Morley et al. 1996, Ewing & Ewing 2002, Feldhaus et al. 2016). In Alaska, releases of smaller Chinook yearlings resulted in a larger size at return (Martin & Wertheimer 1989). For Coho, the trials conducted at Quinsam River Hatchery found no effects, positive effects, and mixed effects depending on the trial, suggesting that the effects of size at release may be confounded with release timing or the year of release (Bilton et al. 1984, Morley et al. 1988, Fagerlund et al. 1989). Furthermore, no effects were observed across five years of Coho releases in Alaska (Linley 2001). However, an analysis of hatchery releases of Coho throughout the northeast Pacific over 26 brood years reported a consistent and significant increase in the body size of adult returns as a result of increased size at release (Hobday & Boehlert 2001).

## Time of release

The timing of hatchery releases determines environmental conditions experienced post-release and thus interactions with mortality factors such as predation and starvation. Release timing can also influence the degree of marine dispersal and growth, given that earlier releases will have more time to disperse and to take advantage of marine prey beneficial to growth (Bilton et al. 1982, Mathews & Ishida 1989). Timing of release was the second most common release strategy examined in the studies reviewed (n = 23; Tables 2-3).

Where effects of release timing were detected, earlier releases of Chinook and later releases of Coho yielded the highest survivals (Tables 7-8; Figures 9-10). The success of earlier Chinook releases has been reported for releases into systems of the Strait of Georgia (Morley et al. 1996) and Puget Sound (Duffy & Beauchamp 2011), as well as into the Columbia River system (Snow 2016). The only report of improved performance from a late Chinook release was from a study in which the smolts were transported down the Columbia River past all major dams, however Chinook that were not barged and migrated naturally performed better when released earlier (Zabel & Williams 2002). Thus, dams and other barriers to fish passage may be affecting the timing of downriver migrations and thus ocean entry.
In contrast, later Coho releases have performed better than early releases into systems of the Strait of Georgia (Labelle et al. 1997), Puget Sound (Quinn et al. 2005), and Columbia River (Hemmingsen et al. 1986, Mathews & Ishida 1989). In Puget Sound, 25 years of Coho releases into Soos Creek illustrated how later releases had higher survivals (Quinn et al. 2005). However, the same study also reported no relationship between release timing and survival for Coho releases from the University of Washington hatchery, and for Chinook from either facility. Although, releases for these experiments only spanned the month of May and might therefore have lacked the sufficient range of release dates required to detect an effect of release timing. In BC, an analysis of 28 years of Coho releases into the Strait of Georgia reported increased survival rates of later release groups at two of five facilities, particularly in recent years (Irvine et al. 2013).

From the limited research conducted in the 1970s and 1980s on the effects of release timing on catch, we found variable effects by species (Tables 7-8; Figure 9). For Chinook, Green and Macdonald (1987) reported the highest catch of their middle release group in early June one year and in late May the next off the west coast of Vancouver Island. However, releases from the east coast of Vancouver Island saw no effect of release timing on catch (Morley et al. 1996). All trials with Coho found a positive response between release timing and catch, with greater catch of later releases (Morley et al. 1988, Mathews & Ishida 1989, Labelle et al. 1997).

Time of release also had different effects on the age of returns across species (Tables 7-9; Figure 9). For Chinook across regions, no effect of the time of release has been observed on return ages or jacking rates (Hard et al. 1985, Morley et al. 1996, Claiborne et al. 2011). Similarly, no effect was seen in the one analysis on Sockeye in Alaska (Wertheimer et al. 1983). Coho, however, have shown a consistent negative response of jacking rates to release time, with lower proportions of jack returns from later releases (Bilton et al. 1982, 1984, Koseki & Fleming 2006). An analysis of 22 years of Coho releases from multiple facilities in Oregon found a significantly higher proportion of jacks returning from early releases than late releases (Koseki & Fleming 2006). Only one trial in the Strait of Georgia reported no effect of release timing on jacking rates (Morley et al. 1988), otherwise studies on Coho releases in BC also reported a negative relationship (Bilton et al. 1982, 1984).

The only information available on the effects of release timing on sex ratios of adult returns comes from trials at Quinsam River Hatchery in BC and a trial at Little Port Walter Hatchery in Alaska from the 1970s and early 1980s. In BC, time of release either had a positive effect on the proportion of male Coho returns or no effect (Bilton et al. 1984, Morley et al. 1988). The positive effect, however, was likely confounded with the higher jacking rates associated with the late release group. Chinook releases from Quinsam saw no effect of release timing on sex ratios (Morley et al. 1996). The Sockeye releases in Alaska also saw no effect (Wertheimer et al. 1983).

One of the more consistent findings between studies across regions was the negative effect of later release timing on adult size at return (Figure 9). Most of these analyses were on Coho, for which later releases have consistently resulted in smaller adults in both BC and Oregon (Bilton et al. 1984, Hemmingsen et al. 1986, Morley et al. 1988, Mathews & Ishida 1989). For instance, from the trials at Quinsam River Hatchery, earlier releases at the end of April came back as adults at almost twice the body size of the late releases in mid June, with a similar trend in the sizes of returning jacks (Morley et al. 1988). The same negative relationship was also seen in Pink salmon. Pink fry were reared in floating estuarine raceways on Baranof Island, AK, for 30, 60 and 90 days prior to release (Martin et al. 1981). The mean length and weight of returning Pink adults decreased with rearing duration with the 90-day treatment having 45% less biomass upon return than those released directly after emergence. A single Sockeye trial in Alaska and a single Chinook trial in BC found no effect of release timing on the size at return (Wertheimer et al. 1983, Morley et al. 1996, respectively).

The timing of hatchery releases determines the conditions experienced by the juveniles during their seaward migrations and in the early marine environment. Chittenden et al. (2010) observed 1.5- to 3-fold greater survival rates when hatchery releases coincided with periods of high marine productivity in the early marine environment. In this case, it's not a question of 'earlier' or 'later' being better, but rather observing the nearshore marine conditions on an annual basis and adjusting release schedules accordingly. Furthermore, a comprehensive analysis of 26 years of Coho releases along their entire North American range compared the effects of marine conditions at the time of release on survival, jack return, and adult return (Hobday & Boehlert 2001). For the Strait of Georgia-Puget Sound region and all releases south along the US coast, environmental conditions (namely mixed layer depth) at the time of hatchery release had a greater impact on survival than at any other time. For Chinook releases from the Central Valley, California, the release date relative to the spring transition date (the initiation of coastal upwelling) was a better predictor than release date alone, with optimal releases observed to be 70-115 days after the spring transition (Satterthwaite et al. 2014). In addition, environmental conditions experienced immediately after release into Puget Sound had a greater impact on survival than the size at release (Quinn et al. 2005). Therefore, it is important to consider 'time of release' as the synchronization of optimal conditions for survival.

## Rearing practices

Rearing conditions at the hatchery can play an important role in determining post-release performance of salmon. Studies have shown that when a given brood year from a single stock are reared across multiple locations, survival rates differ, even when released together at the same time in the same location (Spangenberg et al. 2014, Beckman et al. 2017). Thus it is important to understand the mechanisms at play in the rearing environment. The rearing conditions found in the literature included rearing density (n = 12), container type (including comparisons of traditional and semi-natural rearing; n = 8), and rearing water source (n = 1). Prescribed rearing densities often vary depending on production targets, but also with elevation, water temperature, and target sizes at release. As a result, there was considerable variation in the densities tested across studies, making comparisons of results challenging. However, we assume that these factors were taken into consideration by hatchery staff when selecting the appropriate densities. Therefore, what constitutes 'high' density rearing at one facility may not be high density at another, but we can still compare the two.

Overall, 43% of studies observed a negative relationship between rearing density and survival of Chinook, Coho, and steelhead, while 36% reported no relationship, and 14% had mixed results (Table 10). Only one study reported a positive effect of increased rearing density on survival rates, however this was also the only study in which densities were compared between net pens. Therefore, container type may also play a confounding role in comparison across studies.

In BC, we found a single study on the effects of rearing densities of Coho in Burrow's ponds at Quinsam River Hatchery over two years (Fagerlund et al. 1989). Densities ranged from 15.25-22.70 kg/m3 across four groups in the first year and from 9.16-16.99 kg/m3 across six groups in the second year. Density had a negative effect on returns, but no effect on sex ratios or size at return. Higher densities did result in lower numbers of jacks returning in one of the brood years.

Rearing density has had little effect on other response variables such as catch, return age, sex ratios, or size at return. One study measured the effects on the commercial catch of Chinook and found a decrease in catch with an increase in rearing density (Feldhaus et al. 2016). In addition, single studies reported a negative effect of rearing density on return size of both steelhead in Oregon and Coho in Washington (Banks 1992, Kavanagh & Olson 2014) (Figure 11).

Container type can have a significant effect on hatchery salmon. Experiments ranged from comparing raceway types to assessing the effectiveness of semi-natural rearing. In Oregon, a comparison of earthen and asphalt channels found higher survival of steelhead trout in earthen channels (Tipping 2008a). Another study compared standard concrete raceways to Michigan-style raceways. Michigan raceways were first designed by Boersen & Westers (1986) to increase oxygen flow and improve waste removal. This is achieved by supplementing oxygen at the head of the raceway and adding baffles. Chinook from the Columbia system reared in Michigan-style raceways at higher densities had lower survival, a lower ratio of males to females, and saw an increase in returns of younger Chinook relative to conventional raceways (Clarke et al. 2009). Finally, a comparison of baffled and non-baffled raceways in Washington observed no significant effects on Chinook survival (Brignon et al. 2012).

It is also believed that traditional hatchery rearing practices may cause juvenile salmon to develop behavioural and morphological characteristics that are disadvantageous to post-release survival (Maynard et al. 1995). Thus, a few studies have explored the use of more natural rearing conditions, known as 'semi-natural' rearing, to increase the survival of hatchery fish. Semi-natural conditions can be created using habitat features such as natural ponds with earthen bottoms or traditional raceways painted more natural colours, real or simulated riparian vegetation, submerged woody debris, underwater feeding systems, lower stocking densities, and volitional release (Table 11). We found five studies reporting on the effects of semi-natural rearing, with two from Nitinat River Hatchery on the west coast of Vancouver Island, BC (Brouwer et al. 2014, Doherty & Cox 2018), and three trials from facilities along the Columbia River (Fuss & Byrne 2002, Fast et al. 2008, Tipping 2011). Semi-natural rearing of Chinook in BC resulted in an older age at return, but lower survival rates than conventional hatchery releases (Doherty & Cox 2018). Meanwhile, semi-natural Coho from the same facility had higher survival rates, with a 15% increase in adult production and a 14% decrease in jacking rates relative to conventional rearing (Brouwer et al. 2014). Furthermore, the cost of semi-natural smolt production was only 73% that of conventional smolt production (based on feed and water pumping costs). Coho in WA reared under semi-natural conditions also had slightly higher survival rates, but the difference was not significant (Fuss & Byrne 2002). The semi-natural treatment also resulted in higher jacking rates in two of the three years. For Chinook on the Columbia River, no significant differences have been reported in survival rates of semi-natural and conventionally reared fish. However, jacking rates were also higher in the semi-natural releases (Tipping 2011).

The way in which 'semi-natural' conditions were created was slightly different at each facility and may account for the variable results. In BC, where semi-natural rearing has been effective for more closely matching the older return ages of the natural Chinook population, semi-natural conditions were created in outdoor raceways with lower rearing densities, cooler river temperatures, partial cover, and reduced feeding regimes to align smolt sizes with those of the wild outmigrants (Doherty & Cox 2018). Coho were reared in indoor raceways with lower rearing temperatures, lower densities, and partial netting over the containers to provide areas of shade (Brouwer et al. 2014) (Table 11). Fish were also fed lower rations but in the last three weeks of rearing were fed a natural marine diet of euphausiids via a subsurface jet. They were also exposed to a natural predator (cutthroat trout *Oncorhynchus clarkii*) in the containers, and released volitionally at a smaller, more natural size. Conventional fish were 1.6-2.3 times heavier at release. Relative to semi-natural conditions used in other trials, those at Nitinat River Hatchery were the only ones to rear semi-natural fish at lower temperatures, introduce marine prey into their diets, and release them at smaller sizes (Table 11).

In an analysis of the effects of rearing water, Chinook on the Columbia River had higher survivals and returned at older ages when reared on surface water compared to groundwater (Harstad et al. 2018). No other reports were found comparing the effects of rearing water source.

## Release type

Acclimation can be used to allow fish to recover from the stress of transportation, adjust to marine conditions in a protected environment, and to encourage fish to imprint on, and return to, waters from a specific system. Studies investigating the way in which hatchery fish are released included research on acclimation prior to release (n = 12) and comparisons of volitional and forced releases (n = 5). No studies on the effects of release type were found in BC; the following is a summary from US studies only.

Acclimation was trialed in one of two ways: holding fish in raceways in acclimation facilities on the river of release, or holding fish in seapens in the marine environment, often in the estuary (Table 12). Studies on freshwater acclimation[1] were exclusively from Oregon and yielded mixed results. For steelhead, river acclimated releases had survival rates 33% higher than direct hatchery releases in one of two studies (Clarke et al. 2010), while no effect was reported in a single study on Chinook (Clarke et al. 2016). An important factor in these experiments is the duration of acclimation. A longer period of overwinter acclimation in river water prior to release in the Umatilla River, Oregon, increased survival rates by 27% and returns were slightly older (Clarke et al. 2012). In addition, the extended acclimation period had no effect on the sex ratios of returning Chinook adults.

Most of the sea pen trials were from Alaska, where sea pen-reared Chinook, Coho, Pink, and Sockeye salmon had higher survival rates than the direct hatchery releases by 39-74% (Martin et al. 1981, 2001, Dudiak et al. 1987, Martin & Wertheimer 1987, Linley 2001, Thrower & Joyce 2006, Heard et al. 2013) (Table 12). The success of seapen releases has been attributed to the benefits of allowing smolts time to recover from the stress of transportation and acclimate to estuarine conditions. However, the benefit may also be related to size. A study on Sockeye smolts found that those reared in sea pens had daily growth rates of 5-7% compared to the 2-4% of smolts held in freshwater at the hatchery. The use of sea pens may also be more advantageous in years of low marine survival. Martin et al. (2001) found that Chinook reared in sea pens had more than double the survival rates of freshwater-reared smolts in a year of low marine survival, but that survival rates were comparable in other years. In addition, other release strategies may yield greater benefits than sea pens, as has been shown in one Alaska study on Coho where the time of release had a greater effect on returns (Martin & Wertheimer 1987).

The duration of seapen trials in the literature ranged from only 2 days of acclimation to over-winter acclimation (Thrower & Joyce 2006). Martin et al. 1981 found an increase in survival and size at return for Pink fry reared up to 60 days in seapens, with a decrease beyond 60 days of seapen rearing. However, Thrower & Joyce (2006) found a positive relationship between survival and acclimation period for yearling Chinook salmon. In fact, the highest survivals were measured in those reared in seapens over-winter. This aligns with the respective life histories of Pink and Chinook salmon. As for size, adult Coho from seapen acclimation were larger upon return than those released directly from the hatchery (Linley 2001), however no effect on size was detected for Chinook (Thrower & Joyce 2006). For Chinook from California's Central Valley, seapen acclimation was found to be an important predictor of modelled ocean survival (Satterthwaite et al. 2014).

Of the studies comparing volitional to forced releases in the US, many found either no effect or a negative effect of volitional release (Table 13). In Washington, Chinook released volitionally over a four week period on the Upper Wenatchee River had approximately 20% lower survival than those forced out (Johnson et al. 2015). Meanwhile volitional Coho releases over a 4-8 week period in the Columbia system had similar survival to forced releases, but produced about 50% more jacks (Appleby et al. 2004).

More research has been done into the effects of release type on steelhead trout. Both wild and enhanced steelhead trout can 'residualize' and remain in freshwater rather than migrating to sea. For enhanced steelhead, this behaviour may be a result of hatchery releases occurring before steelhead are physiologically ready to make the transition to saltwater. The practice of releasing hatchery steelhead volitionally can decrease the rate of residualism, or at least facilitate the separation and removal of residuals from the population to reduce any negative impacts on the natural population (Viola & Schuck 1995). However, volitional releases can have mixed effects on adult survival. The only positive effects of volitional release were reported in Washington, where steelhead released volitionally into the Columbia River over 3-11 days had three times the survival rates of forced releases (Snow et al. 2013) (Table 13).

1. Freshwater acclimation is more commonly practiced in the US where many stocks are reared away from their natal streams and rivers and transported to their release locations. The goal of freshwater acclimation is to improve returns to that section of the river by allowing a period for imprinting and adaptation, but also to increase rearing capacity at hatcheries.

In Oregon, steelhead survivals, return ages, and sex ratios were similar for those released volitionally over 14-17 days into the Wallowa River, and those forced into the river (Clarke et al. 2011). However in the Rogue River, Oregon, steelhead released volitionally over a 10 week window had 15% fewer returns than forced releases, with no other effects on age or size at return (Evenson & Ewing 1992). Size and time of release were often recognized as confounding factors in these experiments as they were difficult to synchronize between the two release groups.

## Life stage

Where hatcheries released multiple life stages, the older life stage always exhibited higher survival than the younger life stage (Table 14). No studies were found comparing the success of different life stages released from hatcheries in BC. In Washington, Chinook yearlings released into the Snake River had eight times the survival of subyearlings, the natural life history type (Bugert & Mendel 1997). Coho yearlings in Oregon also exhibited survival two orders of magnitude higher than fry, but had 9.8-17.5% higher incidences of jacks in returns and adult returns were 1.4-2.8% smaller in fork length (Thériault et al. 2010). When compared to an experimental subyearling Coho release, yearlings again had higher survival when both groups were released in July (Hemmingsen et al. 1986). However, yearlings released earlier (May) had lower survival and higher proportions of jacks than subyearlings. Meanwhile in Idaho, a unique experiment was performed using excess eggs from a Sockeye salmon captive brood program. Sockeye reared in the hatchery until the subyearling smolt stage yielded consistently higher recruits per captive brood female than those released as eyed eggs or fry (Johnson et al. 2020).

# DISCUSSION

This review of the effects of hatchery rearing and release strategies on salmon survival, catch, age at maturity, sex ratios, and size at return describes important aspects of the current state of knowledge. It is important to note that this is a review of the literature that met our search criteria. There are a number of studies on the effects of rearing and release strategies on downstream or juvenile survival that could also provide valuable insight, however we chose to focus on studies reporting effects on adults. There are also several early reports that provide descriptive results from some of the first hatchery trials, however with no statistical analyses. While relevant, such results can be misleading, therefore we chose to only report significant results.

Over the past fifty years, the number and type of studies conducted have been highly variable across regions, species, and decades. The majority of the research has been conducted by government agencies, with <20% by scientists from academic institutions. Although the original goal of this review was to summarize the literature available in British Columbia, the low number and diversity of studies available in this region led us to expand our search into the United States. As a result, most of the literature reviewed was from Oregon and Washington. Just over 80% of the studies in the literature were on Chinook and Coho salmon. Size at release was the most well studied strategy, with similar patterns in the results reported across species, regions, and decades. Time of release was the second most common strategy studied, with contrasting results between species and variation in effects over space and time. Below we summarize the main findings for BC, as well as the key themes from the literature, comparisons to previous reviews, and recommendations for future directions.

## Summary of the Literature from British Columbia

Most of what we know about the effects of hatchery rearing and release strategies in BC comes from size and time of release experiments on Coho. In particular, the results of early government experiments in the 1970s and 1980s have been used to define standard release sizes and times throughout the province that are still used today. Several of the results were quadratic in nature, suggesting an 'optimal window' for release sizes and dates. For Coho, an optimal release of 20 g yearlings on June 4 was expected to yield the highest returns (Bilton et al. 1984). For Chinook, optimal releases were of 6-10 g subyearling smolts in May (Morley et al. 1996). However, it is important to note that there were inherent flaws in the study design of some of these early experiments which may have affected the results. Coho were graded into small, medium, and large size classes based on the natural body size distributions in the containers, rather than manipulating size using water temperatures or feed. This method may have selected for heritable traits related to growth and survival, rather than comparing treatments of random groups of fish. These were then released across multiple dates, however sizes within each size class could not be maintained over time, therefore the effects of size and time of release were confounded.

Despite the prescriptive nature of their results, the authors recognized that time and size at release were intricately related to a myriad of other variables, such as fish culture practices, genetics, and meteorological and oceanographic conditions (Bilton et al. 1982, 1984, Morley et al. 1988, 1996). Changes to any of these variables could affect the relationships between size and time at release and thus overall survival and performance. Therefore, they recommended studies be conducted periodically to monitor for possible changes and that release strategies be adapted accordingly. They also acknowledged that their findings varied between facilities, and therefore recommended that each hatchery conduct its own experimentation and fine-tuning of release strategies in order to produce the best results. However, no such experimentation across facilities in BC or periodic re-assessment of these relationships was found in the literature.

Only two references on size and time of release of Coho in BC were found from the last 20 years. Chittenden et al. (2010) explored the effects of release timing relative to early marine conditions on survival of hatchery and wild Coho. They found survival rates to be 1.5 to 3 fold greater when releases were timed with periods of high marine productivity. Consequently, they suggested that seasonal monitoring of chlorophyll-a and water temperatures could help hatcheries forecast the best release windows, rather than scheduling releases for specific dates. They also compared the success of two size groups and found higher survivals of yearling smolts released at 30 g than those released at 25 g, suggesting that the optimal size at release from the 1970s and 1980s were no longer accurate. Furthermore, Irvine et al. (2013) conducted a more comprehensive analysis of the effects of release size and timing using 28 years of Coho release and recovery data from five hatcheries around the Strait of Georgia. Most of the variability in survivals was attributed to the effect of ocean entry year rather than hatchery release strategies. Relationships between parameters also varied between hatcheries, suggesting that optimal sizes and times of release were site-specific. Size at release was an important explanatory variable at each facility, with larger smolts generally having higher survivals, although this relationship also changed over time at one facility. They suggested that the release strategies developed from the 1970s and 1980s are outdated and that hatchery managers should stagger their releases throughout the period of higher survivals of wild out migrants.

Thus, there is an urgent need to re-evaluate the current basis for size and time of release of hatchery fish in BC. To some degree, this need is being addressed. There have been a few experimental trials conducted at facilities around the Strait of Georgia and on the west coast of Vancouver Island since the 1990s, however the results have not been published and it is unclear whether or not hatchery practices have been modified as a result of these experiments. There are currently a number of experimental programs under way at major DFO facilities, including size and time of release experiments on Chinook and Coho salmon at Big Qualicum and Quinsam River hatcheries, as well as a comparison of the yearling and subyearling Chinook releases on the west coast of Vancouver Island. These trials will help guide and improve hatchery practices in southern BC, however no experiments have been done along the central or north coast. Having a plan to assess release strategies at all facilities and adapt strategies as conditions change over time will be essential moving forward.

Limited references were found on the use of other hatchery rearing and release strategies in BC. Semi-natural rearing has only been trialed at one location in BC: Nitinat River Hatchery. At Nitinat, semi-natural rearing has proven to be successful at replicating the wild age structure with older Chinook returns, and increasing Coho adult production by 15% with a 14% reduction in jacking rates at lower cost. Similar trials in the US saw mixed results, although methodology differed between studies. We suggest that there is room to expand upon our understanding and use of semi-natural rearing in BC and that the strategies employed at Nitinat River Hatchery be trialed at other facilities. Rearing density was also only evaluated in a single study on Coho at Quinsam River Hatchery, wherein higher densities resulted in lower survival rates. No studies were found on the effects of life stage released or release type (i.e. volitional versus forced release, acclimation versus direct release). Sea pens are commonly used throughout the province to increase survivals as well as the proportion of hatchery fish in recreational and commercial catches. However, no studies were found in the literature reporting the effectiveness of this practice. While we can gain valuable insight from studies conducted in the US, there is room to expand our understanding of the impacts of rearing and release practices on survival, catch, and biological traits of hatchery salmon in BC.

## Key themes

Certain relationships between release strategies and response variables were more consistent over space and time than others. Where effects of size at release were detected, a larger size at release was related to higher survival rates of Chinook, Coho, and steelhead across regions. However a larger size at release was also related to a younger age at return in 92% of the studies on Coho and 47% of the studies on Chinook. A later date of release resulted in higher survival for Coho in 54% of studies but lower survival for Chinook in 43% of studies. Later releases of Coho had consistently higher catches, but returned as smaller adults than the earlier releases. No relationships were found between the time of Chinook releases and return age, sex ratios, or sizes at return. In Alaska, acclimation in seapens prior to release resulted in higher survivals across multiple salmon species. And finally, where more than one life stage was released, the older stage always had higher survival rates.

However, several studies reported no significant relationships between release strategies and response variables. Of the studies that assessed the impacts of various strategies on sex ratios, ages at return, and sizes at return, more than 50% reported no relationship between the treatment and the outcome. Specifically, 83% reported no effect on sex ratios in returns, 53% reported no effect on adult size at return, and 52% reported no effect on age at return. For studies looking at effects on survival, 32% reported no effect or no relationship; for catch, 44%. This suggests that rearing and release strategies may be more effective at achieving some objectives (i.e. increasing survival) than others (changing the proportion of males or females in the return).

The lack of observed effects of release strategies on some response variables also brings into question the experimental designs used to evaluate release strategies and the timeframes being considered. Isolating single effects in a complex biological system wherein one condition is often confounded by another can be challenging. Random environmental effects associated with the year of release played a significant role in explaining variability in survival rates for many of the studies reviewed. Therefore, a recurrent recommendation was made by authors throughout the literature to examine the effects of release strategies on a hatchery by hatchery basis and to use caution when extrapolating the outcomes from a single study. As stated by Irvine et al. (2013), altering the release sizes and timings of hatchery releases will not reverse the precipitous declines in survival that have been observed in areas like the Strait of Georgia. However, while hatchery managers may not be able to control annual variability, they can use this collective knowledge on the effects of rearing and release strategies to maximize a desired outcome within the limits of natural variability. Indeed, many of the key themes noted above stem from consistent results across years, suggesting that some hatchery practices can yield measurable results in spite of inter-annual variability.

## Comparison to other reviews

This review of the literature on hatchery rearing and release strategies is the most comprehensive to date. However, we found a number of other reviews conducted in the US during our search. A review of release strategies (i.e. time, size, and release location) used for Coho in Oregon, Washington, and BC was conducted by Johnson (1982) summarizing data available from 1933-1978. His review provided a detailed history and evolution of Coho rearing practices that led to many of the practices used today. He noted that many of the early evaluations of hatchery strategies were done during periods of favourable marine conditions for salmon survival and that experiments needed to be re-examined during times of poor ocean productivity. He also found mixed results between studies, but in the Columbia River system, Coho released later or at a larger size were consistently linked to higher returns. Although we did not see this same level of consistency in the subsequent 40 years of literature, later releases and larger sizes at release have continued to be related to higher survival rates for Coho. Johnson also observed that optimal release dates varied by year and recommended that releases be spread throughout a period likely to yield high survivals (e.g. May-July for Columbia River Coho or March-May for coastal Oregon Coho). Optimal release size also varied between facilities and it was recommended that each facility determine its own optimal release size.

Another review of the published literature on anadromous salmon and steelhead throughout the Pacific Northwest was done by Steward and Bjornn (1990) with a particular focus on the Columbia and Snake River populations. Their review focused largely on genetic and ecological concerns associated with enhancement, but also summarized the available literature on rearing densities, age at release, size at release, time of release, and location of release. Rather than synthesizing common findings between studies, they described general concerns and considerations around manipulating release strategies with supporting references from the literature, many of which are captured in our review.

Semi-natural rearing practices have also been reviewed by Maynard et al. (2004). They referenced several studies that have found an increase in post-release survival of semi-natural reared fish. In addition, they summarized the effects of semi-natural rearing on the development of hunting skills, antipredator behaviour, natural habitat preference, as well as stamina. Only three references were included in their review that described the effects on smolt-to-adult survival. Besides the findings of Fuss and Byrne (2002) described in our review, a study on cutthroat trout found survivals were higher when fish were reared in gravel bottom ponds (Tipping 1998). A preliminary study was also referenced which suggested that Coho reared in ponds with camouflage net covers and crate structures had higher survivals (Vander Hagen and Appleby 1998, as referenced by Maynard et al. 2004). Our review includes four additional studies on the effects of semi-natural rearing on survivals that have been conducted since the Maynard et al. review (2004). Of these, two reported mixed effects, one reported positive effects, and one reported negative effects on survival, while all three that measured effects on return ages saw older returns from semi-natural rearing.

Subyearling and yearling releases of hatchery fall Chinook in the Columbia and Snake Rivers have also been reviewed by Poirier & Olson (2017). They summarize the effects of life stage or timing of release on survival, age at return, harvest rates, straying, life history diversity, and ecological impacts from 50 references. The common themes throughout the literature were that yearlings had higher survival rates than subyearlings. Both life stages seemed to have higher survival rates when released later and at larger sizes. Yearlings were commonly found to return at a younger average age than subyearlings, which can reduce the fish available for harvest and broodstock collections. Subyearlings also had higher stray rates. The natural life history strategy in the Columbia and Snake River systems is the subyearling life history, therefore they also describe some of the ecological impacts of releasing yearling fall Chinook.

## Directions for future research

The development of optimal release strategies requires a thorough understanding of the complex relationships between genetics, hatchery rearing and release practices, and environmental conditions. As management objectives are adjusted in response to changing environmental conditions and population dynamics, it is important that we are constantly re-evaluating and updating our state of knowledge on salmon enhancement. For British Columbia and Alaska, much of the research available in the literature is more than 30 years old and should be re-visited. Furthermore, all future studies should cover time scales that capture inter-annual variability (i.e. minimum three brood years). A third of the studies reviewed only spanned one or two years. Only by repeating trials at the same location over time can we begin to determine the effects of hatchery rearing and release strategies relative to other factors driving salmon survivals.

There are a number of rearing and release strategies for which the effects on certain species or response variables are limited or lacking entirely. For instance, the effects of rearing densities on catch, return ages, sex ratios, and sizes at return have been mostly analysed in a single study for each species, some of which are more than 30 years old. For example, rearing density was reported to have negative effects on Coho return ages from a trial in BC in the early 1980s, but no other studies have reported on this relationship. Size at release trials, though the most common release strategy studied, have been largely focused on Coho and performed in Washington. Very little is known about the effects of size at release of Chinook, particularly in Alaska, BC, and California, where only single publications were found on the subject. Similarly, only one study was found on the effects of release timing on Chinook survival outside of Washington. This provides an avenue for focusing future hatchery trials to improve our understanding of their effects on Chinook, specifically.

Interactions between rearing conditions, release strategies, environmental conditions, genetics, and management practices are complex, making it difficult to isolate the effects of a single factor. Thus, confounding factors are often present when studying the effects of hatchery strategies. For instance, late releases are sometimes also larger in body size than conventional releases. Rearing containers can influence rearing densities, which in turn can determine the size of the fish at release. At a larger scale, outcomes of these strategies may be confounded by the dominating environmental regimes at the time of the study (e.g. only looking at effects during periods of high or low marine productivity). The presence of confounding factors can weaken the strength of the conclusions reported in the literature. In order to improve our understanding of the effects of hatchery strategies, care should be taken when designing release experiments to isolate effects.

Another area lacking research is the effect of hatchery rearing and release strategies on fisheries. One of the primary management objectives for the high production hatcheries in BC is to produce fish for harvest. Catch and survival are inherently linked; survival rates are calculated using exploitation rates, and the exploitation rates are driven largely by management actions responding to trends in survival. Yet survival rates alone cannot inform the effects of enhancement on fisheries. Catch was the least reported response variable, analysed in just 13% of the references captured in this review. In addition, most of these analyses were performed in the 1970s and 1980s. Two more recent studies have used CWT data from the Regional Mark Information System (RMIS) to analyse the relationships between hatchery release strategies and catch (Satterthwaite et al. 2014, Feldhaus et al. 2016). The RMIS is an online repository that provides release information and expanded recoveries for the Pacific coast. Data from the RMIS could be used to improve our understanding of the effects of hatchery practices on providing harvest opportunities.

Another area for future research is the role of diversified hatchery release strategies. Recent research has shown that the times of release and sizes at release of hatchery fish have narrowed significantly over the last 65 years, which could have negative implications for both hatchery and wild fish (Irvine et al. 2013, Huber & Carlson 2015, Nelson et al. 2019). Having diversified release strategies creates resilience to environmental uncertainty by spreading risk across multiple releases. Narrowing release strategies towards a single 'optimal' release date or size risks eliminating the natural diversity of the population and the ability to adapt to changing environmental conditions. Therefore, it is important that results from one-off experimental releases not be used to establish fixed hatchery practices. Optimal rearing and release strategies should be moving targets that change with environmental conditions and management objectives while minimizing risk to natural populations. Diversifying release strategies may, in itself, be the best strategy.

In summary, a considerable amount of research has been conducted on the effects of hatchery rearing and release strategies, however efforts have varied over space and time. Trials to determine the best strategies for meeting management objectives should be standard practice at all facilities and should be re-visited regularly. More research needs to be done in BC, as well as in Alaska, Idaho, and California, to understand the effects of rearing and release strategies in those regions. In particular, studies on Chinook outside of Washington and Oregon and studies on steelhead outside of Oregon would help to expand our understanding of the effects of release strategies and their use as management tools across a wider range of populations. Understudied hatchery strategies are areas for future research, such as comparisons between life stages, rearing water types, semi-natural rearing, or the use of seapens. There is also more to learn about the effects of hatchery strategies on response variables other than survival, such as catch, sex ratios, and size at return.

Photo by: Sam James

# TABLES

**Table 1:** The 76 publications investigating associations between hatchery strategies and responses in returning adult salmon included in our systematic literature review.

| Reference | Affil.[§] | Brood Years | Country | Region | System[θ] | Species | Life Stage | Strategy | Response |
|---|---|---|---|---|---|---|---|---|---|
| Appleby et al. (2004) | WDFW | 1983-1985 | US | WA | Columbia | Coho | yearling | release | age[*], survival |
| Banks (1992) | US FWS | 1981-1982 | US | WA | Columbia | Coho | yearling | rearing | sex, size, survival |
| Banks (1994) | US FWS | 1982-1985 | US | WA | Columbia | Chinook | yearling | rearing | age, sex, size, survival |
| Banks & LaMotte (2002) | US FWS | 1989-1992 | US | WA | Columbia | Chinook | subyearling | rearing | age, sex, size, survival |
| Beckman et al. (1999) | NOAA | 1988-1990 | US | OR | Columbia | Chinook | yearling | size | survival |
| Beckman et al. (2017) | NOAA | 2008-2010 | US | OR | Columbia | Chinook | smolt | size, rearing | survival |
| Beeman & Novotny (1995) | NOAA | 1985-1986 | US | WA | Columbia | Chinook | subyearling | rearing | survival |
| Bilton et al. (1982) | DFO | 1973 | Canada | BC | SoG | Coho | yearling | size, time | age[*], survival |
| Bilton et al. (1984) | DFO | 19788 | Canada | BC | SoG | Coho | yearling | size, time | age[*], catch, sex, size, survival |
| Brignon et al. (2012) | US FWS | 2002-2004 | US | WA | Columbia | Chinook | yearling | rearing | survival |
| Brouwer et al. (2014) | DFO | 2002-2004 | Canada | BC | WCVI | Coho | yearling | rearing | age[*], size, survival |
| Bugert et al. (1997) | WDFW | 1983-1989 | US | WA | Columbia | Chinook | subyearling, yearling | life stage | survival |
| Chittenden et al. (2010) | UiT | 2004-2006 | Canada | BC | SoG | Coho | yearling | time, size | survival |
| Claiborne et al. (2011) | NOAA | 2000-2003 | US | OR | Columbia | Chinook | yearling | size, time | age, survival |
| Clarke et al. (2009) | ODFW | 1996-2001 | US | OR | Columbia | Chinook | yearling | rearing | age, sex, survival |
| Clarke et al. (2010) | ODFW | 1986-1995 | US | OR | Columbia | steelhead | yearling | release | age, sex, survival |
| Clarke et al. (2011) | ODFW | 1995-1998 | US | OR | Columbia | steelhead | smolt | release | age, sex, survival |
| Clarke et al. (2012) | ODFW | 1999-2004 | US | OR | Columbia | Chinook | yearling | release | age, sex, survival |
| Clarke et al. (2013) | ODFW | 1998-1999 | US | OR | Columbia | Chinook | smolt | rearing | age, sex, survival |

Part 1. Pacific salmon hatchery release strategies in Canada and the United States

| Reference | Affil.[§] | Brood Years | Country | Region | System[θ] | Species | Life Stage | Strategy | Response |
|---|---|---|---|---|---|---|---|---|---|
| Clarke et al. (2014) | ODFW | 1984-1989 | US | OR | Columbia | steelhead | yearling | size | survival |
| Clarke et al. (2016) | ODFW | 2002-2007 | US | OR | Columbia | Chinook | subyearling | release | survival |
| Doherty & Cox (2018) | Consultant | 2005-2012 | Canada | BC | WCVI | Chinook | subyearling | rearing | age, sex, survival |
| Dudiak et al. (1987) | ADFG | 1980 | US | AK | Kachemak Bay | Chinook | subyearling | release | survival |
| Duffy & Beauchamp (2011) | UW | 1996-2006 | Canada | BC | Puget Sound | Chinook | subyearling | time, size | survival |
| Evenson & Ewing (1992) | ODFW | 1977-1980 | US | OR | Rogue | steelhead | smolt | release | age, size, survival |
| Ewing & Ewing (2002) | Consultant | 1989-1992 | US | OR | Columbia | Chinook | yearling | size | age, size |
| Fagerlund et al. (1989) | DFO | 1981-1982 | Canada | BC | SoG | Coho | yearling | rearing, size | age*, sex, size, survival |
| Fast et al. (2008) | Consultant | 1997-2001 | US | WA | Columbia | Chinook | yearling | rearing | survival |
| Feldhaus et al. (2016) | ODFW | 1988-1998 | US | OR | Columbia | Chinook | yearling | size, rearing | age, catch, sex, size, survival |
| Fuss and Byrne (2002) | WDFW | 1995-1997 | US | WA | Columbia | Coho | yearling | rearing, time | survival |
| Green & MacDonald (1987) | Dal | 1972-1977 | Canada | BC | SoG | Chinook | subyearling | time, size | catch |
| Hager & Noble (1976) | WDFW | 1962 | US | WA | Puget Sound | Coho | yearling | size | age, survival |
| Hard et al. (1985) | NOAA | 1976 | US | AK | Chickamin, Unuk | Chinook | yearling | size, time | age* |
| Harstad et al. (2014) | NOAA | 1999-2010 | US | WA | Columbia | Chinook | yearling | size | age* |
| Harstad et al. (2018) | NOAA | 2006-2009 | US | WA | Columbia | Chinook | yearling | rearing, size | age, survival |
| Heard et al. (2013) | NOAA | 1987-1991 | US | AK | Chatham Strait | Sockeye | subyearling | release | survival |
| Hemmingsen et al. (1986) | ODFW | 1977-1978 | US | OR | Columbia | Coho | subyearling, yearling | life stage | size, survival |
| Hobday & Boehlert (2001) | NOAA | 1971-1996 | Both | NE Pacific | North Pacific | Coho | yearling | size | size, survival |
| Hopley et al. (1993) | WDFW | 1980-1982 | US | WA | Columbia | Coho | yearling | rearing, size | age*, survival |
| Irvine et al. (2013) | DFO | 1977-2004 | Canada | BC | SoG | Coho | yearling | size, time | survival |

| Reference | Affil.§ | Brood Years | Country | Region | Systemθ | Species | Life Stage | Strategy | Response |
|---|---|---|---|---|---|---|---|---|---|
| Johnson et al. (2015) | WDFW | 2003-2005 | US | WA | Columbia | Chinook | yearling | release | survival |
| Johnson et al. (2020) | IDFG | 2004-2012 | US | ID | Columbia | Sockeye | egg, fry, smolt | life stage | age, sex, size, survival |
| Kavanagh & Olson (2014) | US FWS | 2004-2006 | US | OR | Columbia | steelhead | yearling | rearing | age, size, survival |
| Kenaston et al. (2001) | ODFW | 1991-1993 | US | OR | Siuslaw | steelhead | yearling | release | survival |
| Koseki & Fleming (2006) | Hokudai | 1976-1997 | US | OR | Oregon coast | Coho | yearling | size, time | age*, survival |
| Labelle et al. (1997) | UBC | 1983-1985 | Canada | BC | SoG | Coho | yearling | time | catch, survival |
| Linley (2001) | NSRAA | 1990-1994 | US | AK | Baranof Island | Coho | yearling | release, size | size, survival |
| Martin et al. (1981) | NOAA | 1975 | US | AK | Baranof Island | Pink | fry | release, time | size, survival |
| Martin & Wertheimer (1987) | NOAA | 1974-1975 | US | AK | Baranof Island | Coho | yearling | release | size, survival |
| Martin & Wertheimer (1989) | NOAA | 1978 | US | AK | Unuk | Chinook | yearling | rearing, size | age, size, survival |
| Martin et al. (2001) | NOAA | 1976-1985 | US | AK | Baranof Island | Chinook | yearling | release | survival |
| Mathews & Buckley (1976) | UW | 1964-1970 | US | WA | Puget Sound | Coho | yearling | size | catch, survival |
| Mathews & Ishida (1989) | UW | 1979-1982 | US | OR | Columbia | Coho | yearling | time, size | catch, size, survival |
| Morley et al. (1988) | DFO | 1979-1981 | Canada | BC | SoG | Coho | yearling | size, time | age*, catch, sex, size, survival |
| Morley et al. (1996) | DFO | 1981-1982 | Canada | BC | SoG | Chinook | subyearling | size, time | age, catch, sex, size, survival |
| Olson & Paiya (2013) | US FWS | 2000-2002 | US | OR | Columbia | Chinook | yearling | rearing | survival |
| Passolt & Anderson (2013) | UW | 1998-2009 | US | ID | Columbia | Chinook | yearling | size | survival |
| Quinn et al. (2005) | UW | 1968-1997 | US | WA | Puget Sound | Coho, Chinook | subyearling, yearling | size, time | survival |
| Sabal et al. (2016) | UCSC | 1998-2009 | US | CA | Central Valley | Chinook | yearling | size | survival |
| Satterthwaite et al. (2014) | NOAA, UC | 1979-2009 | US | CA | Central Valley | Chinook | subyearling | release, size, time | catch, survival |

| Reference | Affil.§ | Brood Years | Country | Region | System$^{\theta}$ | Species | Life Stage | Strategy | Response |
|---|---|---|---|---|---|---|---|---|---|
| Slaney et al. (1993) | MoE | 1980-1982 | Canada | BC | SoG | steelhead | yearling | size | survival |
| Snow et al. (2013) | WDFW | 2002-2004 | US | WA | Columbia | steelhead | yearling | release | survival |
| Snow (2016) | WDFW | 2003-2006 | US | WA | Columbia | Chinook | subyearling | time | survival |
| Spangenberg et al. (2014) | NOAA | 2008-2010 | US | OR | Columbia | Chinook | subyearling | rearing, size | age* |
| Thériault et al. (2010) | OSU | 2001-2003 | US | OR | Umpqua | Coho | fry, yearling | life stage | age*, size, survival |
| Thompson et al. (2018) | OSU | 1997-2009 | US | OR | Columbia | steelhead | smolt | size | survival |
| Thrower & Joyce (2006) | NOAA | 1992 | US | AK | Chickamin, Unuk | Chinook | yearling | release | catch, size, survival |
| Tipping (1997) | WDFW | 1981-1982 | US | WA | Columbia | steelhead | yearling | size | survival |
| Tipping et al. (2004) | WDFW | 1994-2000 | US | WA | Columbia | steelhead | yearling | rearing | survival |
| Tipping (2008a) | WDFW | 2001-2003 | US | WA | Columbia, Puget Sound | Coho | yearling | size | age*, sex, survival |
| Tipping (2008b) | WDFW | 2001-2003 | US | WA | Puget Sound | steelhead | yearling | rearing | survival |
| Tipping (2011) | WDFW | 2000-2003 | US | WA | Columbia, Puget Sound | Chinook | subyearling, yearling | rearing, size | age*, sex, survival |
| Vøllestad et al. (2004) | UW | 1950-2000 | US | WA | Puget Sound | Chinook, Coho | subyearling | size | age* |
| Wertheimer et al. (1983) | NOAA | 1973 | US | AK | Baranof Island | Sockeye | yearling | time | age, sex, size, survival |
| Zabel & Williams (2002) | NOAA | 1993-1994 | US | WA | Columbia | Chinook | yearling | size, time | survival |
| Zaugg (1989) | NOAA | 1977-1981 | US | WA | Columbia | Chinook | subyearling | size, time | survival |

§ADFG = Alaska Department of Fish and Game, Dal = Dalhousie University, DFO = Fisheries and Oceans Canada, Hokudai = Hokkaido University, IDFG = Idaho Department of Fish and Game, MoE = Ministry of Environment, NOAA = National Oceanic and Atmospheric Administration, NSRAA = Northern Southeast Aquaculture Association, ODFW = Oregon Department of Fish and Wildlife, OSU = Oregon State University, UBC = University of British Columbia, UC = University of California, UCSC = University of California Santa Cruz, UiT = University of Tromso, UW = University of Washington, USFWS = United States Fish and Wildlife Service, WDFW = Washington Department of Fish and Wildlife

θ Systems are rivers unless otherwise indicated.

age* = study reported proportion of jacks

**Table 2:** The number (%) of references that investigated each hatchery strategy and response by region. Note that percentages have been rounded and so totals may differ from values in the table.

| | Treatment | | | | | Response | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Region** | **Life Stage** | **Rearing** | **Release** | **Size** | **Time** | **Age** | **Catch** | **Sex** | **Size** | **Survival** | **Total** |
| AK | 0 (0) | 1 (1) | 7 (9) | 3 (4) | 4 (5) | 3 (4) | 1 (1) | 1 (1) | 6 (8) | 9 (12) | 10 (13) |
| BC | 0 (0) | 3 (4) | 0 (0) | 9 (12) | 8 (11) | 7 (9) | 5 (7) | 5 (7) | 5 (7) | 11 (14) | 12 (16) |
| WA | 1 (1) | 12 (16) | 3 (4) | 13 (17) | 6 (8) | 10 (13) | 1 (1) | 5 (7) | 3 (4) | 25 (33) | 27 (36) |
| OR | 2 (3) | 7 (9) | 6 (8) | 10 (13) | 4 (5) | 13 (17) | 2 (3) | 6 (8) | 7 (9) | 20 (26) | 22 (29) |
| CA | 0 (0) | 0 (0) | 1 (1) | 2 (3) | 1 (1) | 0 (0) | 1 (1) | 0 (0) | 0 (0) | 2 (3) | 2 (3) |
| ID | 1 (1) | 0 (0) | 0 (0) | 1 (1) | 0 (0) | 1 (1) | 0 (0) | 1 (1) | 1 (1) | 2 (3) | 2 (3) |
| NE Pacific | 0 (0) | 0 (0) | 0 (0) | 1 (1) | 0 (0) | 0 (0) | 0 (0) | 0 (0) | 1 (1) | 1 (1) | 1 (1) |
| **Total** | **4 (5)** | **23 (30)** | **17 (22)** | **39 (51)** | **23 (31)** | **34 (45)** | **11 (14)** | **18 (24)** | **23 (30)** | **70 (92)** | **76 (100)** |

**Table 3:** The number (%) of references that investigated each hatchery strategy and response by species. Note that two studies included both Chinook and Coho and are therefore counted twice, giving a total of 78.

| | Treatment | | | | | Response | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **Species** | **Life Stage** | **Rearing** | **Release** | **Size** | **Time** | **Age** | **Catch** | **Sex** | **Size** | **Survival** | **Total** |
| Chinook | 1 (1) | 15 (20) | 7 (9) | 21 (28) | 10 (13) | 17 (22) | 5 (7) | 9 (12) | 7 (9) | 32 (42) | 38 (50) |
| Coho | 2 (3) | 5 (7) | 3 (4) | 16 (21) | 12 (16) | 12 (16) | 5 (7) | 5 (7) | 11 (14) | 23 (30) | 24 (32) |
| Pink | 0 (0) | 0 (0) | 1 (1) | 0 (0) | 1 (1) | 0 (0) | 0 (0) | 0 (0) | 1 (1) | 1 (1) | 1 (1) |
| Sockeye | 1 (1) | 0 (0) | 1 (1) | 0 (0) | 1 (1) | 2 (3) | 0 (0) | 2 (3) | 2 (3) | 3 (4) | 3 (4) |
| Steelhead | 0 (0) | 3 (4) | 5 (7) | 4 (5) | 0 (0) | 4 (5) | 0 (0) | 2 (3) | 2 (3) | 12 (16) | 12 (16) |
| **Total** | **4 (5)** | **23 (30)** | **17 (22)** | **41 (54)** | **24 (32)** | **35 (45)** | **10 (13)** | **17 (22)** | **23 (31)** | **70 (93)** | **78 (100)** |

**Table 4:** Summary of studies on the effects of **Chinook** size at release on survival, catch, and/or age. The 'Response' describes the relationship between an increase in size at release and the response variable. Responses can be either positive (green), negative quadratic (green), negative (red), positive quadratic (red), mixed (yellow), or none.

| Region | System | Hatchery | BY (n) | Life Stage | Size Type | Response Variable | Response | Ref |
|---|---|---|---|---|---|---|---|---|
| AK | Chickamin | Little Port Walter | 1976-1976 (1) | yearling | weight | age* | none | *Hard et al. (1985)* |
| AK | Unuk | Little Port Walter | 1978-1978 (1) | yearling | weight | size | positive | *Martin & Wertheimer (1989)* |
| AK | Unuk | Little Port Walter | 1978-1978 (1) | yearling | weight | age | negative | *Martin & Wertheimer (1989)* |
| AK | Unuk | Little Port Walter | 1978-1978 (1) | yearling | weight | survival | positive | *Martin & Wertheimer (1989)* |
| BC | Strait of Georgia VI | Robertson Creek | 1972-1977 (6) | subyearling | weight | catch | positive | *Green & MacDonald (1987)* |
| BC | Strait of Georgia VI | Quinsam River | 1981-1982 (2) | subyearling | weight | age | none | *Morley et al. (1996)* |
| BC | Strait of Georgia VI | Quinsam River | 1981-1982 (2) | subyearling | weight | catch | none | *Morley et al. (1996)* |
| BC | Strait of Georgia VI | Quinsam River | 1981-1982 (2) | subyearling | weight | %males | none | *Morley et al. (1996)* |
| BC | Strait of Georgia VI | Quinsam River | 1981-1982 (2) | subyearling | weight | size | none | *Morley et al. (1996)* |
| BC | Strait of Georgia VI | Quinsam River | 1981-1982 (2) | subyearling | weight | survival | mixed | *Morley et al. (1996)* |
| WA | Puget Sound | University of Washington | 1950-2000 (50) | subyearling | weight | age* | none | *Vøllestad et al. (2004)* |
| WA | Puget Sound | Soos Creek | 1968-1997 (21) | subyearling | weight | survival | none | *Quinn et al. (2005)* |
| WA | Puget Sound | University of Washington | 1968-1997 (30) | subyearling | weight | survival | none | *Quinn et al. (2005)* |
| WA | Columbia | Spring Creek | 1977-1981 (5) | subyearling | weight | survival | none | *Zaugg (1989)* |
| WA | Columbia | NA | 1993-1994 (2) | yearling | length | survival | positive | *Zabel & Williams (2002)* |
| WA | Puget Sound | multiple | 1996-2006 (4) | subyearling | weight | survival | positive | *Duffy & Beauchamp (2011)* |
| WA | Columbia | Cle Elum | 1999-2010 (12) | yearling | length | age* | negative | *Harstad et al. (2014)* |
| WA | Columbia | Multiple | 2003-2009 (7) | yearling | length | age* | none | *Harstad et al. (2014)* |
| WA | Columbia | Eastbank[1] | 2006-2009 (4) | yearling | length | age* | negative | *Harstad et al. (2014)* |
| WA | Columbia | Eastbank[2] | 2006-2009 (4) | yearling | length | age* | negative | *Harstad et al. (2014)* |
| WA | Columbia | Kalama Falls | 2000-2002 (3) | yearling | length | age* | mixed | *Tipping (2011)* |
| WA | Columbia | Kalama Falls | 2000-2002 (3) | yearling | length | %males | none | *Tipping (2011)* |
| WA | Columbia | Kalama Falls | 2000-2002 (3) | yearling | length | survival | positive | *Tipping (2011)* |

| Region | System | Hatchery | BY (n) | Life Stage | Size Type | Response Variable | Response | Ref |
|---|---|---|---|---|---|---|---|---|
| WA | Columbia | Washougal | 2001-2003 (3) | subyearling | length | age* | none | *Tipping (2011)* |
| | | | | | | %males | none | |
| | | | | | | survival | none | |
| WA | Columbia | Priest Rapids | 2002-2003 (2) | subyearling | length | age* | negative | |
| | | | | | | %males | none | |
| | | | | | | survival | positive | |
| WA | Puget Sound | Wallace River | 2002-2002 (1) | subyearling | length | age* | none | |
| | | | | | | %males | positive | |
| | | | | | | survival | positive | |
| WA | Columbia | Eastbank | 2006-2009 (4) | yearling | weight | age | negative | *Harstad et al. (2018)* |
| | | | | | | survival | none | |
| OR | Columbia | multiple | 1988-1990 (3) | yearling | length | survival | none | *Beckman et al. (1999)* |
| OR | Columbia | Lookingglass | 1988-1998 (10) | yearling | weight | age | none | *Feldhaus et al. (2016)* |
| | | | | | | catch | negative | |
| | | | | | | %males | none | |
| | | | | | | size | none | |
| | | | | | | survival | none | |
| OR | Columbia | Willamette | 1989-1992 (4) | yearling | length | age | negative | *Ewing & Ewing (2002)* |
| | | | | | | size | none | |
| OR | Columbia | Willamette | 2000-2003 (4) | yearling | length | age | negative | *Claiborne et al. (2011)* |
| | | | | | | survival | none | |
| OR | Columbia | multiple | 2008-2010 (3) | subyearling | length | survival | positive | *Beckman et al. (2017)* |
| OR | Columbia | multiple | 2008-2010 (3) | subyearling | length | age* | none | *Spangenberg et al. (2014)* |
| CA | Central Valley | Feather River | 1979-2009 (28) | subyearling | weight | catch | positive | *Satterthwaite et al. (2014)* |
| CA | Central Valley | multiple | 1998-2009 (10) | yearling | weight | survival | positive | *Sabal et al. (2016)* |
| ID | Columbia | multiple | 1998-2009 (6) | yearling | length | survival | positive | *Passolt & Anderson (2013)* |

Eastbank[1] = combination of Methow-Okanogan stocks
Eastbank[2] = Wenatchee River stock
age* = study reported proportion of jacks, but presented here as effects on age (i.e. negative age response = increase in jacks)

**Table 5:** Summary of studies on the effects of **Coho** size at release on survival, catch, age at return, sex ratios, and size at return. The 'Response' describes the relationship between an increase in size at release and the response variable. Responses can be either positive (green), negative quadratic (green), negative (red), positive quadratic (red), mixed (yellow), or none.

| Region | System | Hatchery | BY (n) | Life Stage | Size Type | Response Variable | Response | Ref |
|---|---|---|---|---|---|---|---|---|
| AK | Baranof Island | Hidden Falls | 1990-1994 (5) | yearling | weight | size | none | *Linley (2001)* |
| | | | | | | survival | none | |
| BC | Strait of Georgia VI | Rosewall Creek | 1973-1973 (1) | yearling | weight | age* | negative | *Bilton et al. (1982)* |
| | | | | | | survival | positive quadratic | |
| BC | Strait of Georgia VI | Quinsam River | 1978-1978 (1) | yearling | weight | age* | negative | *Bilton et al. (1984)* |
| | | | | | | catch | mixed | |
| | | | | | | %males | mixed | |
| | | | | | | size | mixed | |
| | | | | | | survival | mixed | |
| BC | Strait of Georgia VI | Quinsam River | 1981-1982 (2) | yearling | weight | age* | negative | *Fagerlund et al. (1989)* |
| | | | | | | %males | mixed | |
| | | | | | | size | positive | |
| | | | | | | survival | positive | |
| BC | Strait of Georgia VI | Quinsam River | 1981-1982 (2) | subyearling | weight | age | none | *Morley et al. (1996)* |
| | | | | | | catch | none | |
| | | | | | | %males | none | |
| | | | | | | size | none | |
| | | | | | | survival | mixed | |
| BC | Strait of Georgia | Quinsam River, Puntledge River, Rosewall Creek, Big Qualicum River, Inch Creek, Chilliwack River | 1977-2004 (28) | yearling | weight | survival | positive | *Irvine et al. (2013)* |
| BC | Strait of Georgia VI | Quinsam River | 1979-1979 (1) | yearling | weight | age* | negative | *Morley et al. (1988)* |
| | | | | | | catch | none | |
| | | | | | | %males | mixed | |
| | | | | | | size | mixed | |
| | | | | | | survival | mixed | |
| BC | Strait of Georgia VI | Quinsam River | 1981-1981 (1) | yearling | weight | age* | negative | *Morley et al. (1988)* |
| | | | | | | catch | none | |
| | | | | | | %males | none | |
| | | | | | | size | none | |
| | | | | | | survival | none | |

| Region | System | Hatchery | BY (n) | Life Stage | Size Type | Response Variable | Response | Ref |
|---|---|---|---|---|---|---|---|---|
| BC | Strait of Georgia | multiple | 2004-2006 (3) | yearling | weight | survival | positive | *Chittenden et al. (2010)* |
| WA | Puget Sound | Minter Creek | 1962-1962 (1) | yearling | length, weight | age | negative | *Hager & Noble (1976)* |
| | | | | | | survival | positive | |
| WA | Puget Sound | multiple | 1964-1970 (5) | yearling | weight | catch | negative quadratic | *Mathews & Buckley (1976)* |
| | | | | | | survival | positive | |
| WA | Puget Sound | Soos Creek | 1968-1997 (25) | yearling | weight | survival | none | *Quinn et al. (2005)* |
| | | University of Washington | 1968-1997 (30) | subyearling | weight | survival | none | |
| WA | Puget Sound | University of Washington | 1970-2000 (30) | subyearling | weight | age | negative | *Vøllestad et al. (2004)* |
| WA | Columbia | Cowlitz Salmon | 1980-1982 (3) | yearling | length | age* | negative | *Hopley et al. (1993)* |
| | | | | | | survival | none | |
| | | Washougal | 1980-1982 (3) | yearling | length | survival | none | |
| WA | Puget Sound | Marblemount | 2001-2003 (3) | yearling | length | age* | none | *Tipping (2008)* |
| | | | | | | %males | none | |
| | | | | | | survival | none | |
| | Columbia | Toutle | 2001-2001 (1) | yearling | length | age* | negative | |
| | | | | | | %males | positive | |
| | | | | | | survival | positive | |
| | Puget Sound | George Adams | 2002-2003 (2) | yearling | length | age* | negative | |
| | | | | | | %males | none | |
| | | | | | | survival | negative | |
| OR | Oregon | Bonneville, Eagle Creek, Big Creek, Klaskanine, Nehalem, Trask, Salmon River, Fall Creek, Cole Rivers | 1976-1997 (22) | yearling | weight | age* | negative | *Koseki & Fleming (2006)* |
| | | | | | | survival | positive | |
| OR | Columbia | Big Creek | 1979-1979 (1) | yearling | length, weight | survival | none | *Mathews & Ishida (1989)* |
| | | Anadromous Inc Facility Coos Bay | 1982-1982 (1) | yearling | length, weight | survival | positive | |
| NE Pacific | North Pacific | NA | 1971-1996 (26) | yearling | length | size | positive | *Hobday & Boehlert (2001)* |
| | | | | | | survival | mixed | |

age* = study reported proportion of jacks, but presented here as effects on age (i.e. negative age response = increase in jacks)

**Table 6:** Summary of studies on the effects of **steelhead** size at release on survival. The 'Response' describes the relationship between an increase in size at release and the response variable. Responses can be either positive (green), negative quadratic (green), negative (red), positive quadratic (red), mixed (yellow), or none.

| Region | System | Hatchery | BY (n) | Life Stage | Size Type | Response Variable | Response | Ref |
|---|---|---|---|---|---|---|---|---|
| BC | Strait of Georgia ML | Chilliwack River | 1980-1982 (3) | yearling | weight | survival | positive | *Slaney et al. (1993)* |
| WA | Columbia | Cowlitz Trout | 1981-1982 (2) | yearling | length | survival | positive | *Tipping (1997)* |
| OR | Columbia | Irrigon | 1984-1989 (5) | yearling | weight | survival | positive | *Clarke et al. (2014)* |
| OR | Columbia | Parkdale | 1997-2009 (2) | smolt | length | survival | positive | *Thompson et al. (2018)* |

**Table 7:** Summary of studies on the effects of **Chinook** time of release on survival, catch, age, proportion of male returns, and/or size at return. The 'Response' describes the relationship between a later time of release and the response variable. Responses can be either positive (green), negative quadratic (green), negative (red), positive quadratic (red), mixed (yellow), or none.

| Region | System | Hatchery | BY (n) | Life Stage | Response Variable | Response | Ref |
|---|---|---|---|---|---|---|---|
| AK | Unuk | Little Port Walter | 1976-1976 (1) | yearling | age* | none | *Hard et al. (1985)* |
| BC | Strait of Georgia VI | Robertson Creek | 1972-1977 (6) | subyearling | catch | negative quadratic | *Green & MacDonald (1987)* |
| BC | Strait of Georgia VI | Quinsam River | 1981-1982 (2) | subyearling | age | none | *Morley et al. (1996)* |
| | | | | | catch | none | |
| | | | | | %males | none | |
| | | | | | size | none | |
| | | | | | survival | negative | |
| WA | Puget Sound | Soos Creek | 1968-1997 (21) | subyearling | survival | none | *Quinn et al. (2005)* |
| WA | Puget Sound | University of Washington | 1968-1997 (30) | subyearling | survival | none | |
| WA | Columbia | Spring Creek | 1977-1981 (5) | subyearling | survival | none | *Zaugg (1989)* |
| WA | Columbia | NA | 1993-1994 (2) | yearling | survival | mixed | *Zabel & Williams (2002)* |
| WA | Puget Sound | multiple | 1996-2006 (4) | subyearling | survival | negative | *Duffy & Beauchamp (2011)* |
| WA | Columbia | Wells | 2003-2006 (4) | subyearling | survival | negative | *Snow (2016)* |
| OR | Columbia | Willamette | 2000-2003 (4) | yearling | age | none | *Claiborne et al. (2011)* |
| CA | Central Valley | Feather River | 1979-2009 (28) | subyearling | catch | mixed | *Satterthwaite et al. (2014)* |

age* = study reported proportion of jacks, but presented here as effects on age (i.e. negative age response = increase in jacks)

**Table 8:** Summary of studies on the effects of **Coho** time of release on survival, catch, age, proportion of male returns, and/or size at return. The 'Response' describes the relationship between a later time of release and the response variable. Responses can be either positive (green), negative quadratic (green), negative (red), positive quadratic (red), mixed (yellow), or none.

| Region | System | Hatchery | BY (n) | Life Stage | Response Variable | Response | Ref |
|---|---|---|---|---|---|---|---|
| AK | Baranof Island | Little Port Walter | 1974-1975 (2) | yearling | survival | positive | *Martin & Wertheimer (1987)* |
| BC | Strait of Georgia VI | Rosewall Creek | 1973-1973 (1) | yearling | age* | positive | *Bilton et al. (1982)* |
| | | | | | survival | positive quadratic | |
| BC | Strait of Georgia VI | Quinsam River | 1978-1978 (1) | yearling | age* | positive | *Bilton et al. (1984)* |
| | | | | | size | negative | |
| | | | | | %males | none | |
| | | | | | survival | negative quadratic | |
| BC | Strait of Georgia | multiple | 1977-2004 (28) | yearling | survival | mixed | *Irvine et al. (2013)* |
| BC | Strait of Georgia VI | Quinsam River | 1979-1979 (1) | yearling | age* | none | *Morley et al. (1988)* |
| | | | | | catch | positive | |
| | | | | | %males | positive | |
| | | | | | size | negative | |
| | | | | | survival | negative quadratic | |
| BC | Strait of Georgia VI | multiple | 1983-1985 (2) | yearling | catch | positive | *Labelle et al. (1997)* |
| | | | | | survival | positive | |
| BC | Strait of Georgia | multiple | 2004-2006 (3) | yearling | survival | mixed | *Chittenden et al. (2010)* |
| WA | Puget Sound | Soos Creek | 1968-1997 (25) | yearling | survival | positive | *Quinn et al. (2005)* |
| WA | Puget Sound | University of Washington | 1968-1997 (30) | subyearling | survival | none | |
| WA | Columbia | Elochoman | 1995-1997 (3) | yearling | survival | none | *Fuss & Byrne (2002)* |
| OR | Oregon | multiple | 1976-1997 (22) | yearling | age* | positive | *Koseki & Fleming (2006)* |
| OR | Columbia | Big Creek | 1977-1978 (2) | yearling | size | negative | *Hemmingsen et al. (1986)* |
| | | | | | survival | positive | |
| OR | Columbia | Big Creek | 1979-1979 (1) | yearling | catch | positive | *Mathews and Ishida (1989)* |
| | | | | | size | negative | |
| | | | | | survival | negative quadratic | |
| OR | Columbia | Anadromous Inc Facility Coos Bay | 1982-1982 (1) | yearling | catch | positive | *Mathews and Ishida (1989)* |
| | | | | | size | negative | |
| | | | | | survival | positive | |

age* = study reported proportion of jacks, but presented here as effects on age (i.e. negative age response = increase in jacks)

**Table 9:** Summary of studies on the effects of **Sockeye and Pink** time of release on survival, age, proportion of male returns, and/or size at return. The 'Response' describes the relationship between a later time of release and the response variable. Responses can be either positive (green), negative quadratic (green), negative (red), positive quadratic (red), mixed (yellow), or none.

| Region | System | Hatchery | BY (n) | Species | Life Stage | Response Variable | Response | Ref |
|---|---|---|---|---|---|---|---|---|
| AK | Baranof Island | Little Port Walter | 1973-1973 (1) | Sockeye | yearling | age | none | *Wertheimer et al. (1983)* |
| | | | | | | %males | none | |
| | | | | | | size | none | |
| | | | | | | survival | positive | |
| AK | Baranof Island | Little Port Walter | 1975-1975 (1) | Pink | fry | size | negative | *Martin et al. (1981)* |
| | | | | | | survival | negative quadratic | |

**Table 10:** Summary of studies reporting the effects of density on survival, catch, age at return, size at return, and/or proportion of males in returns. Density groups represent the mean (± SD) extracted from each study and broken into 'Low', 'Medium' (Med), and 'High' releases where three or more densities were compared. However, 'Response' reflects the relationships found between an increase in rearing density and the response variables and can be either positive (green), negative (red), mixed (yellow), or none.

| Region | System | Hatchery | BY (n) | Species | Life Stage | Density Groups (kg/m³) | Container Type | Response Variable | Response | Ref |
|---|---|---|---|---|---|---|---|---|---|---|
| AK | Unuk | Little Port Walter | 1978-1978 (1) | Chinook | yearling | Low: 8.73 (± 1.51)<br>Med: 14.77 (± 2.60)<br>High: 22.30 (± 2.00) | raceway | age | none | *Martin & Wertheimer (1989)* |
| | | | | | | | | size | none | |
| | | | | | | | | survival | negative | |
| BC | Strait of Georgia VI | Quinsam River | 1983-1984 (2) | Coho | yearling | Low: 10.60 (± 1.27)<br>Med: 16.19 (± 0.69)<br>High: 22.48 (± 0.22) | Burrow's pond | age* | mixed | *Fagerlund et al. (1989)* |
| | | | | | | | | %males | none | |
| | | | | | | | | size | none | |
| | | | | | | | | survival | negative | |
| WA | Columbia | Cowlitz Salmon | 1980-1982 (3) | Coho | yearling | Low: 21.95 (± 2.63)<br>Med: 26.34 (± 2.14)<br>High: 33.26 (± 2.53) | raceway | survival | none | *Hopley et al. (1993)* |
| | | Washougal | | | | Low: 3.55 (± 0.42)<br>Med: 5.10 (± 0.75)<br>High: 7.42 (± 0.74) | raceway | survival | none | |
| WA | Columbia | Willard | 1981-1982 (2) | Coho | yearling | Low: 14.08 (± 0.55)<br>Med: 29.68 (± 1.58)<br>High: 41.72 (± 3.50) | raceway | %males | negative | *Banks (1992)* |
| | | | | | | | | size | none | |
| | | | | | | | | survival | negative | |
| WA | Columbia | Carson | 1982-1985 (4) | Chinook | yearling | Low: 13.33 (± 1.65)<br>Med: 26.22 (± 3.17)<br>High: 37.01 (± 7.00) | raceway | age | none | *Banks (1994)* |
| | | | | | | | | %males | none | |
| | | | | | | | | size | none | |
| | | | | | | | | survival | negative | |
| WA | Columbia | Rock Creek, Drano Lake | 1985-1986 (2) | Chinook | sub-yearling | Low: 1.14 (± 0.18)<br>Med: 2.66 (± 0.43)<br>High: 4.21 (± 0.16) | net pen | survival | positive | *Beeman & Novotny (1995)* |

| Region | System | Hatchery | BY (n) | Species | Life Stage | Density Groups (kg/m3) | Container Type | Response Variable | Response | Ref |
|---|---|---|---|---|---|---|---|---|---|---|
| WA | Columbia | Spring Creek | 1989-1992 (4) | Chinook | sub-yearling | Low: 4.07 (± 0.62)<br>Med 1: 7.83 (± 1.15)<br>Med 2: 11.4 (± 1.86)<br>High: 15.23 (± 2.31) | Burrow's pond | age | none | *Banks & LaMotte (2002)* |
| | | | | | | | | %males | none | |
| | | | | | | | | size | none | |
| | | | | | | | | survival | mixed | |
| WA | Columbia | Skamania | 1994-1996 (3) | steelhead | yearling | Low: 18.38 (± 0.79)<br>High: 27.71 (± 1.71) | raceways | survival | none | *Tipping et al. (2004)* |
| | | Merwin | 1998-2000 (3) | | | Low: 3.85 (± 0.38)<br>High: 5.61 (± 0.67) | pond | survival | negative | |
| OR | Columbia | Looking-glass | 1988-1998 (10) | Chinook | yearling | Low: 4.47 (± 1.55)<br>Med: 19.48 (± 2.19) | raceway | age | none | *Feldhaus et al. (2016)* |
| | | | | | | | | catch | negative | |
| | | | | | | | | survival | none | |
| OR | Columbia | Umatilla | 1998-1999 (2) | Chinook | sub-yearling | Low: 23.65 (± 5.45)<br>Med: 35.25 (± 6.95)<br>High: 44.25 (± 8.05) | Michigan-style raceway | age | none | *Clarke et al. (2013)* |
| | | | | | | | | %males | none | |
| | | | | | | | | survival | none | |
| OR | Columbia | Warm Springs | 2000-2002 (3) | Chinook | yearling | Low: 4.24 (± 0.47)<br>Med: 6.27 (± 0.52)<br>High: 8.42 (± 0.64) | raceway | survival | mixed | *Olson & Paiya (2013)* |
| OR | Columbia | Eagle Creek | 2004-2006 (3) | steelhead | yearling | Low: 13.64 (± 1.26)<br>Med: 23.43 (± 2.56)<br>High: 35.21 (± 3.52) | raceway | age | none | *Kavanagh & Olson (2014)* |
| | | | | | | | | size | negative | |
| | | | | | | | | survival | negative | |

age* = study reported proportion of jacks, but presented here as effects on age (i.e. negative age response = increase in jacks)

**Table 11:** Summary of studies on the effects of semi-natural rearing on survival, age, and/or return size. Semi-natural rearing conditions described are relative to the control group. Responses can be either higher (green), lower (red), mixed (yellow), or none.

| Region | System | Hatchery | BY (n) | Species | Life Stage | Container Type | Water Source | Water Temp | Density | Cover | Size at Release | Feed | Response Variable | Response | Ref |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| BC | West Coast Vancouver Island | Nitinat River | 2002-2004 (3) | Coho | yearling | indoor concrete raceway | blend | lower | lower | shade cloth | smaller | surface then subsurface, lower ration | age* | higher | *Brouwer et al. (2014)* |
| | | | | | | | | | | | | | size | mixed | |
| | | | | | | | | | | | | | survival | higher | |
| BC | West Coast Vancouver Island | Nitinat River | 2005-2012 (8) | Chinook | sub-yearling | outdoor raceway | river | lower | same (both low) | shade cloth, branches | smaller | surface, lower ration | age | higher | *Doherty & Cox (2018)* |
| | | | | | | | | | | | | | %males | none | |
| | | | | | | | | | | | | | survival | lower | |
| WA | Columbia | Elocho-man | 1995-1997 (3) | Coho | yearling | earthen-bottom pond | blend | same | lower | large woody debris, pit rock, riparian vegetation | same | surface, lower or same ration | survival | none | *Fuss & Byrne (2002)* |
| WA | Columbia | Cle Elum | 1997-2001 (5) | Chinook | yearling | camouflage-painted concrete raceways | blend | same | same | surface nets and submerged conifers | same | sub-surface, same ration | survival | mixed | *Fast et al. (2008)* |
| WA | Columbia | Kalama Falls | 2000-2000 (1) | Chinook | yearling | semi-natural rearing pond | NA | NA | NA | NA | NA | NA | age* | higher | *Tipping (2011)* |
| | | | | | | | | | | | | | survival | mixed | |

**Table 12:** Summary of studies on the effects of acclimation prior to release on survival, catch, and/or size at return. Responses can be either higher (green), lower (red), mixed (yellow), or none.

| Region | System | Hatchery | BY (n) | Species | Life Stage | Treatment | Duration (days) | Response Variable | Response | Ref |
|---|---|---|---|---|---|---|---|---|---|---|
| AK | Baranof Island | Little Port Walter | 1975-1975 (1) | Pink | fry | sea pen | 30-90 | survival | higher | *Martin et al. (1981)* |
| | | | | | | | | size | higher | |
| AK | Chatham Strait | NA | 1987-1991 (5) | Sockeye | sub-yearling | sea pen | 6-65 | survival | higher | *Heard et al. (2013)* |
| AK | Kache-mak Bay | Halibut Cove Lagoon Saltwater Rearing Facility | 1980-1980 (1) | Chinook | sub-yearling | sea pen | 14 | survival | higher | *Dudiak et al. (1987)* |
| AK | Baranof Island | Hidden Falls | 1990-1994 (5) | Coho | yearling | sea pen | 14-35 | survival | higher | *Linley (2001)* |
| | | | | | | | | size | higher | |
| OR | Columbia | Irrigon | 1986-1995 (10) | steelhead | yearling | acclimation facility | 16-57 | age | none | *Clarke et al. (2010)* |
| | | | | | | | | %males | none | |
| | | | | | | | | survival | higher | |
| OR | Siuslaw | Alsea Trout | 1991-1993 (3) | steelhead | yearling | acclimation facility | 30 | survival | none | *Kenaston et al. (2001)* |
| OR | Columbia | Umatilla | 2002-2007 (5) | Chinook | sub-yearling | acclimation facility | 14-21 | survival | none | *Clarke et al. (2016)* |
| CA | Central Valley | Feather River | 1979-2009 (28) | Chinook | sub-yearling | sea pen | NA | catch | none | *Satterthwaite et al. (2014)* |
| | | | | | | | | survival | none | |

**Table 13:** Summary of studies on the effects of volitional hatchery releases on survival, age at return, size at return, and/or sex ratios in returns. The 'Response' describes the relationship between a volitional release and the response variable relative to a forced release. Responses are either higher (green), lower (red), mixed (yellow), or none.

| Region | System | Hatchery | BY (n) | Species | Life Stage | Response Variable | Response | Ref |
|---|---|---|---|---|---|---|---|---|
| WA | Columbia | Kalama Falls | 1983-1985 (3) | Coho | yearling | survival | none | *Appleby et al. (2004)* |
| | | | | | | age* | lower | |
| WA | Columbia | Grays River | 1983-1985 (3) | Coho | yearling | survival | none | |
| | | | | | | age* | lower | |
| WA | Columbia | Wells | 2002-2004 (3) | steelhead | yearling | survival | higher | *Snow et al. (2013)* |
| WA | Columbia | Chiwawa River | 2003-2005 (3) | Chinook | yearling | survival | lower | *Johnson et al. (2015)* |
| OR | Rogue | Cole Rivers | 1977-1980 (4) | steelhead | smolt | survival | lower | *Evenson & Ewing (1992)* |
| | | | | | | age | none | |
| | | | | | | size | none | |
| OR | Columbia | Irrigon | 1995-1998 (4) | steelhead | smolt | survival | none | *Clarke et al. (2011)* |
| | | | | | | %males | none | |
| | | | | | | age | none | |

age* = study reported proportion of jacks, but presented here as effects on age (i.e. negative age response = increase in jacks)


Photo by: Mitch Miller

**Table 14:** Summary of studies on the difference in survival, age at maturity, size at maturity, and/or proportion of males in returns between life stages released. The naturally life history type of the population is bolded. Responses for each life stage are summarized as either being higher (green), lower (red), mixed (yellow), or none for each life stage.

| Region | System | Hatchery | BY (n) | Species | Life Stage | Response Variable | Response | Ref |
|---|---|---|---|---|---|---|---|---|
| WA | Columbia | Lyons Ferry | 1983-1989 (6) | Chinook | **subyearling** | survival | lower | *Bugert et al. (1997)* |
| | | | | | yearling | survival | higher | |
| OR | Columbia | Big Creek | 1977-1978 (2) | Coho | subyearling | size | mixed | *Hemmingsen et al. (1986)* |
| | | | | | subyearling | survival | mixed | |
| | | | | | **yearling** | size | mixed | |
| | | | | | **yearling** | survival | higher | |
| OR | Umpqua | Rock Creek | 2001-2003 (3) | Coho | fry | age* | higher | *Thériault et al. (2010)* |
| | | | | | fry | size | higher | |
| | | | | | fry | survival | lower | |
| | | | | | **yearling** | age* | lower | |
| | | | | | **yearling** | size | lower | |
| | | | | | **yearling** | survival | higher | |
| ID | Columbia | Multiple | 2004-2012 (9) | Sockeye | **egg** | age | higher | *Johnson et al. (2020)* |
| | | | | | **egg** | %males | none | |
| | | | | | **egg** | size | none | |
| | | | | | **egg** | survival | lower | |
| | | | | | fry | age | higher | |
| | | | | | fry | %males | none | |
| | | | | | fry | size | none | |
| | | | | | fry | survival | lower | |
| | | | | | yearling | age | lower | |
| | | | | | yearling | %males | higher | |
| | | | | | yearling | size | none | |
| | | | | | yearling | survival | higher | |

age* = study reported proportion of jacks, but presented here as effects on age (i.e. negative age response = increase in jacks)

# FIGURES

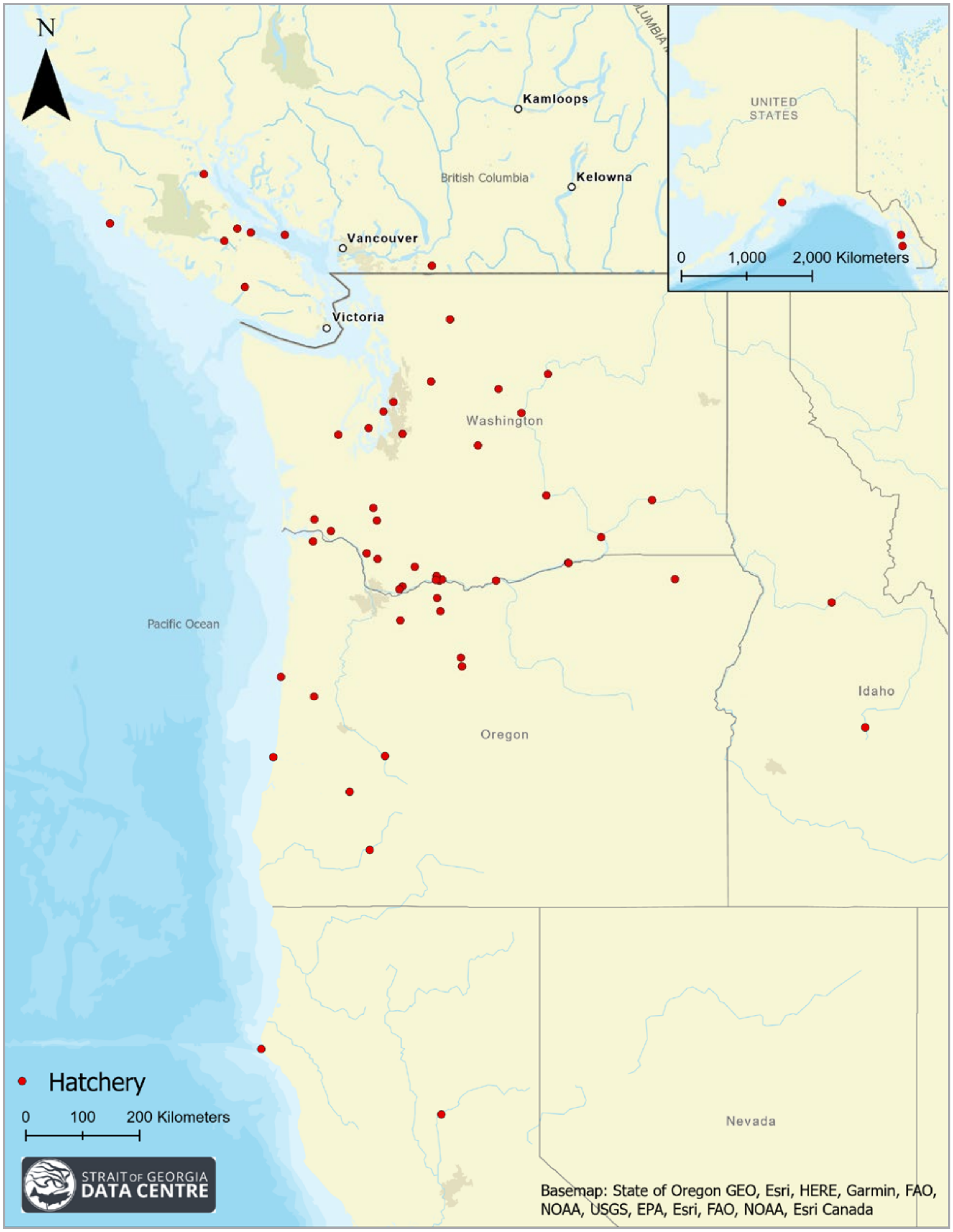


Figure 1: Distribution of hatchery and enhancement facilities captured by the literature search that have reported on experimental releases between 1970 and 2020 (produced by Jake Dingwall, Strait of Georgia Datacentre).

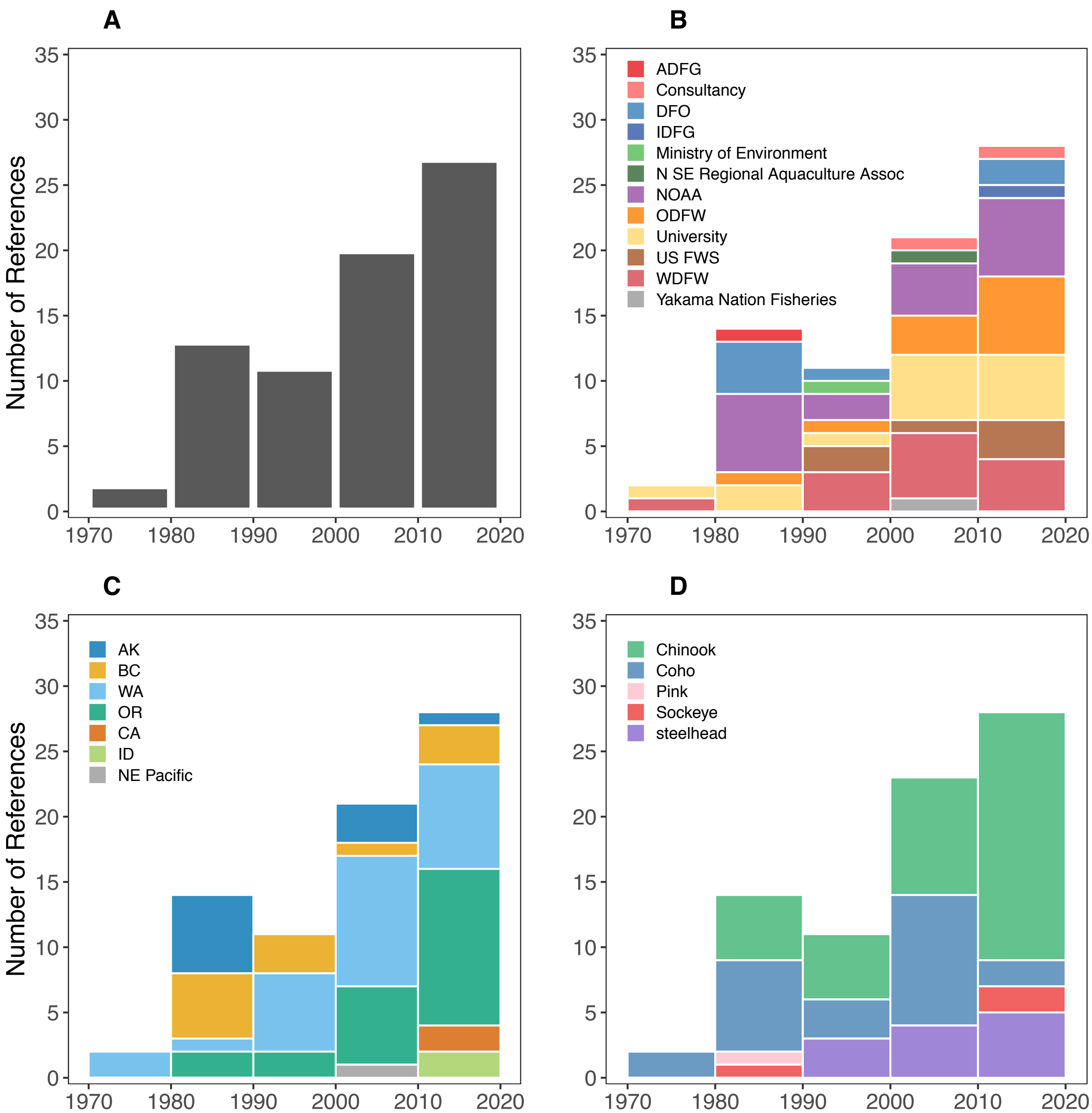


**Figure 2:** Number of references found on the effects of hatchery release strategies per decade of publication (A). References by decade of publication are distinguished by the author affiliation (B), region of the study (C), and species of interest (D).

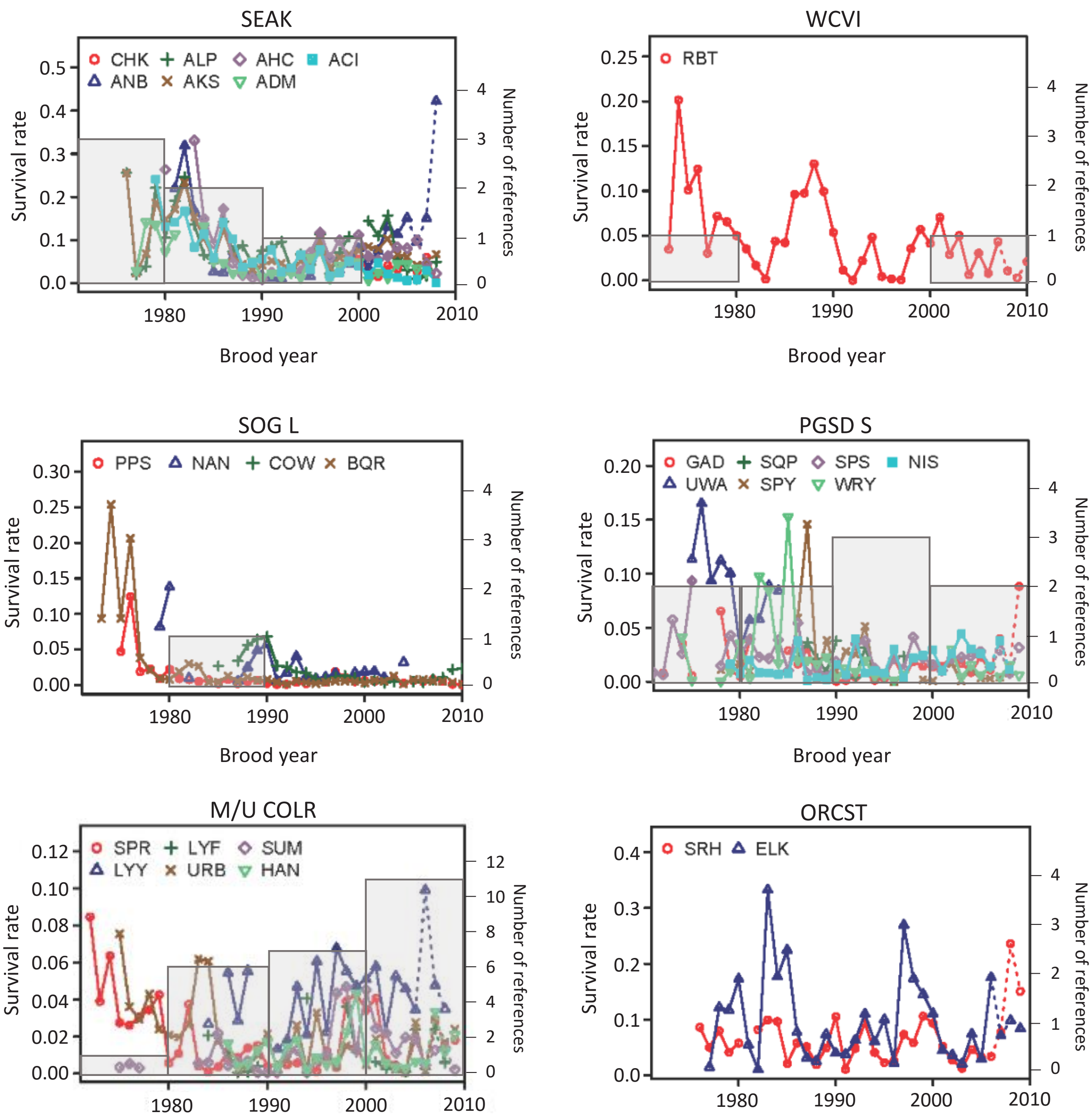


Figure 3: Number of references (grey bars) reporting on Chinook release strategies over time relative to the changes in Chinook survival rates. SEAK = Southeast Alaska, WCVI = west coast Vancouver Island, M/U COLR = middle and upper Columbia River (Washington and Oregon), SOG L = lower Strait of Georgia, ORCST = Oregon coast, PGSD S = southern Puget Sound. Each plotted line represents an indicator stock from that region. Note the difference in the survival rate y-axis between plots and that the M/U COLR secondary axis (number of references) is tripled relative to the others. Figure has been adapted from (Riddell et al. 2013).

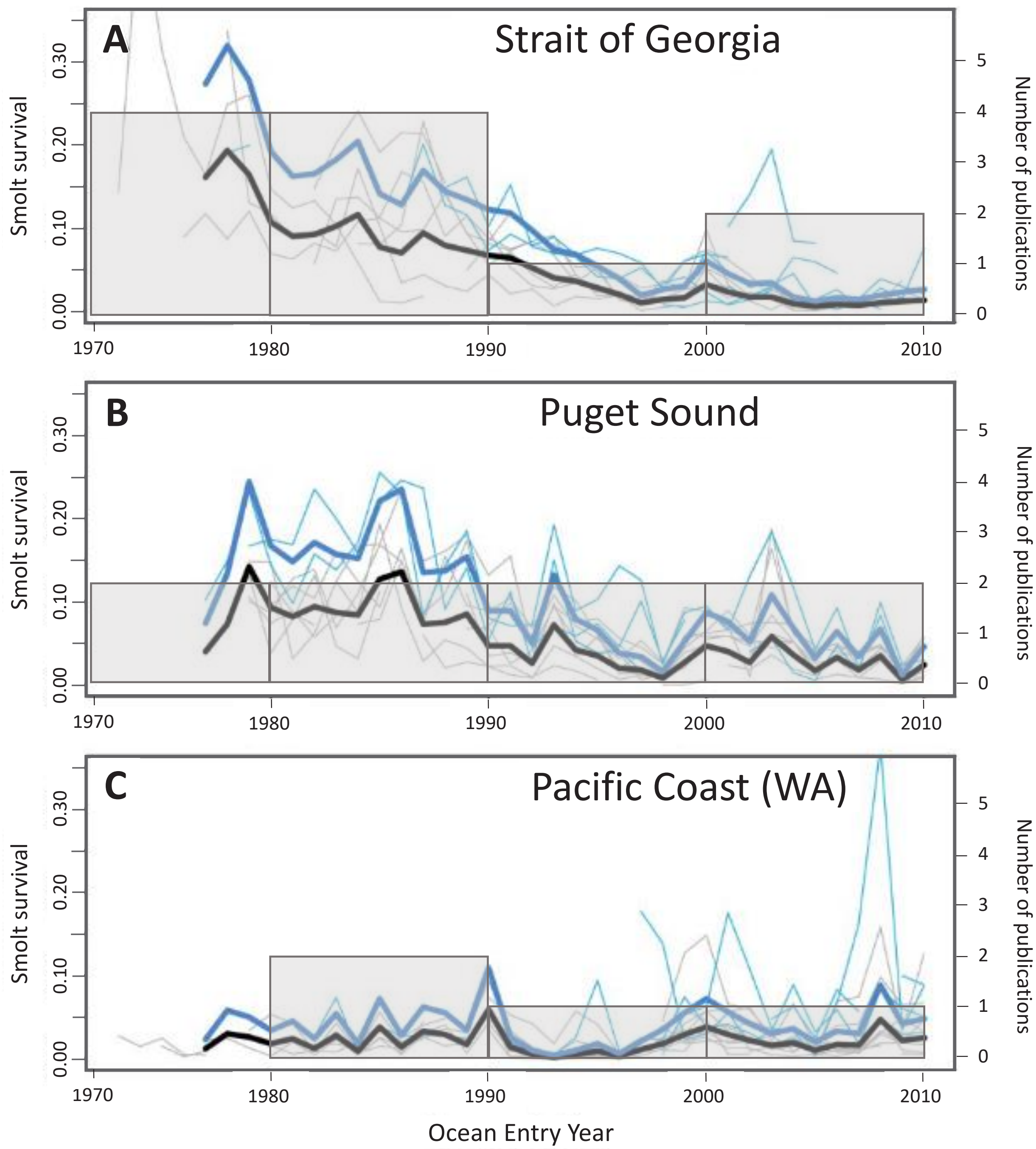


**Figure 4:** The number of references (grey bars) reporting on Coho release strategies over time relative to trends in logit-transformed survival of Coho populations from the Strait of Georgia (A), Puget Sound (B), and the Washington Coast (C). The thin grey lines represent individual hatchery populations while the thick black line shows predicted survival for hatchery populations in each region. The thin blue lines represent individual wild populations and the thick blue line represents the predicted survival for wild populations in each region. Figure has been adapted from Zimmerman et al. 2015.

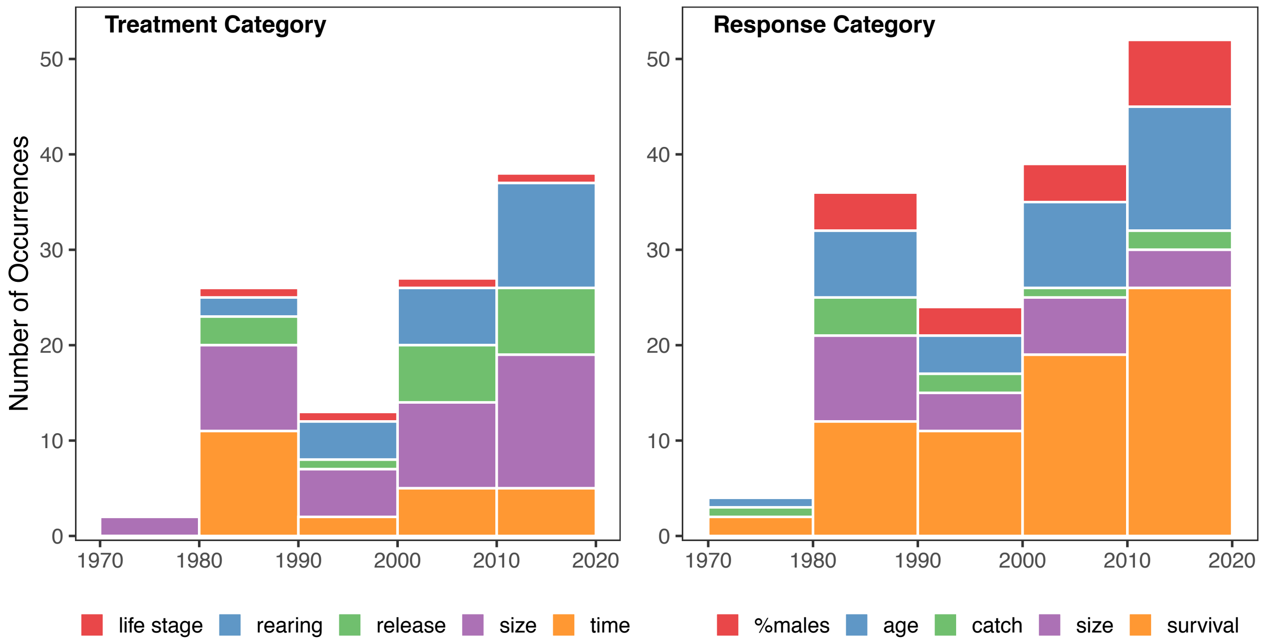


**Figure 5:** Number of occurrences of each treatment or response variable in studies in the literature published and reviewed over the last 50 years.

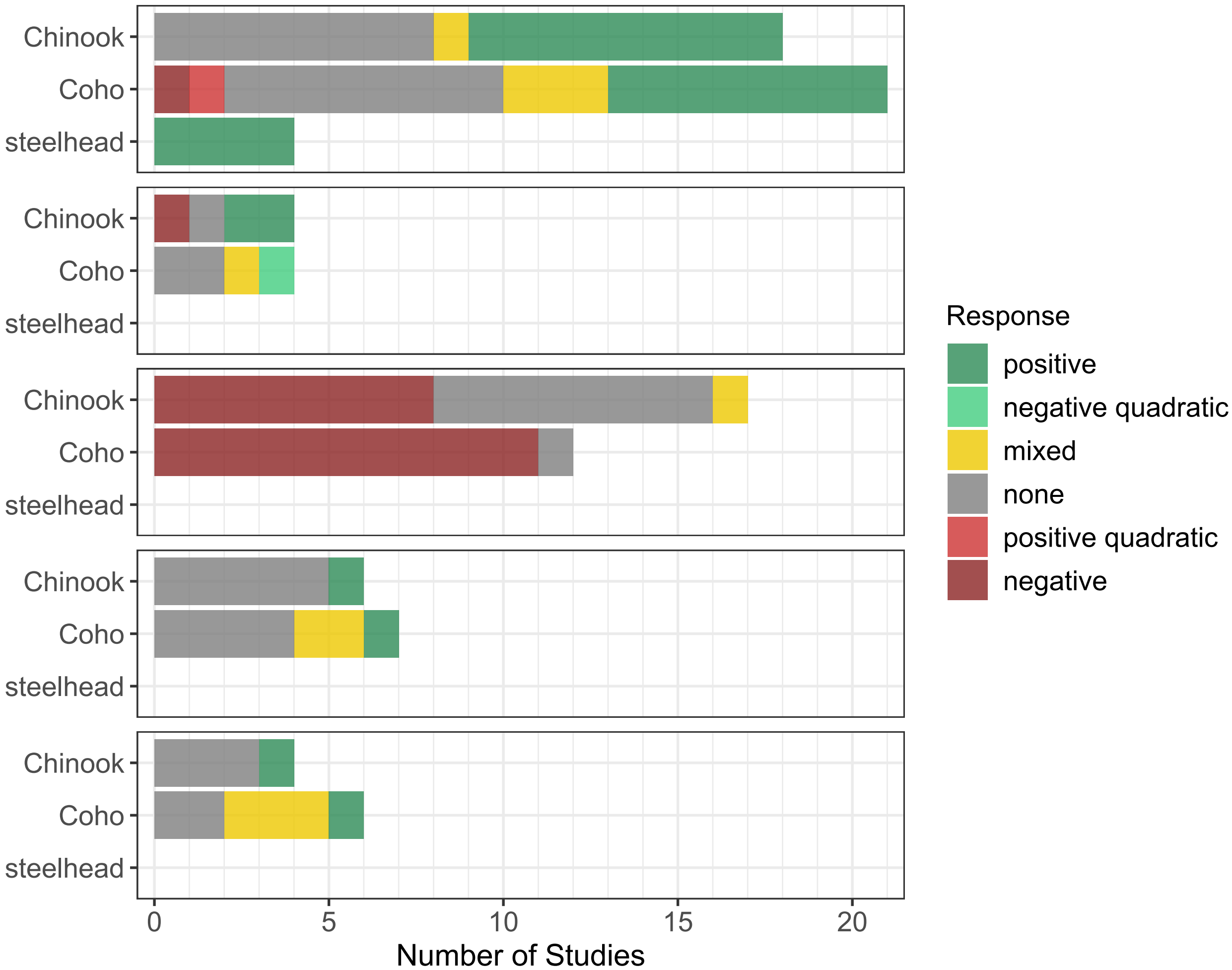


**Figure 6:** Summary of the effects of increased size at release on survival, catch, age at return, proportion of males in returns, and size at return for Chinook, Coho, and steelhead showing the number of studies reporting each relationship in the literature.

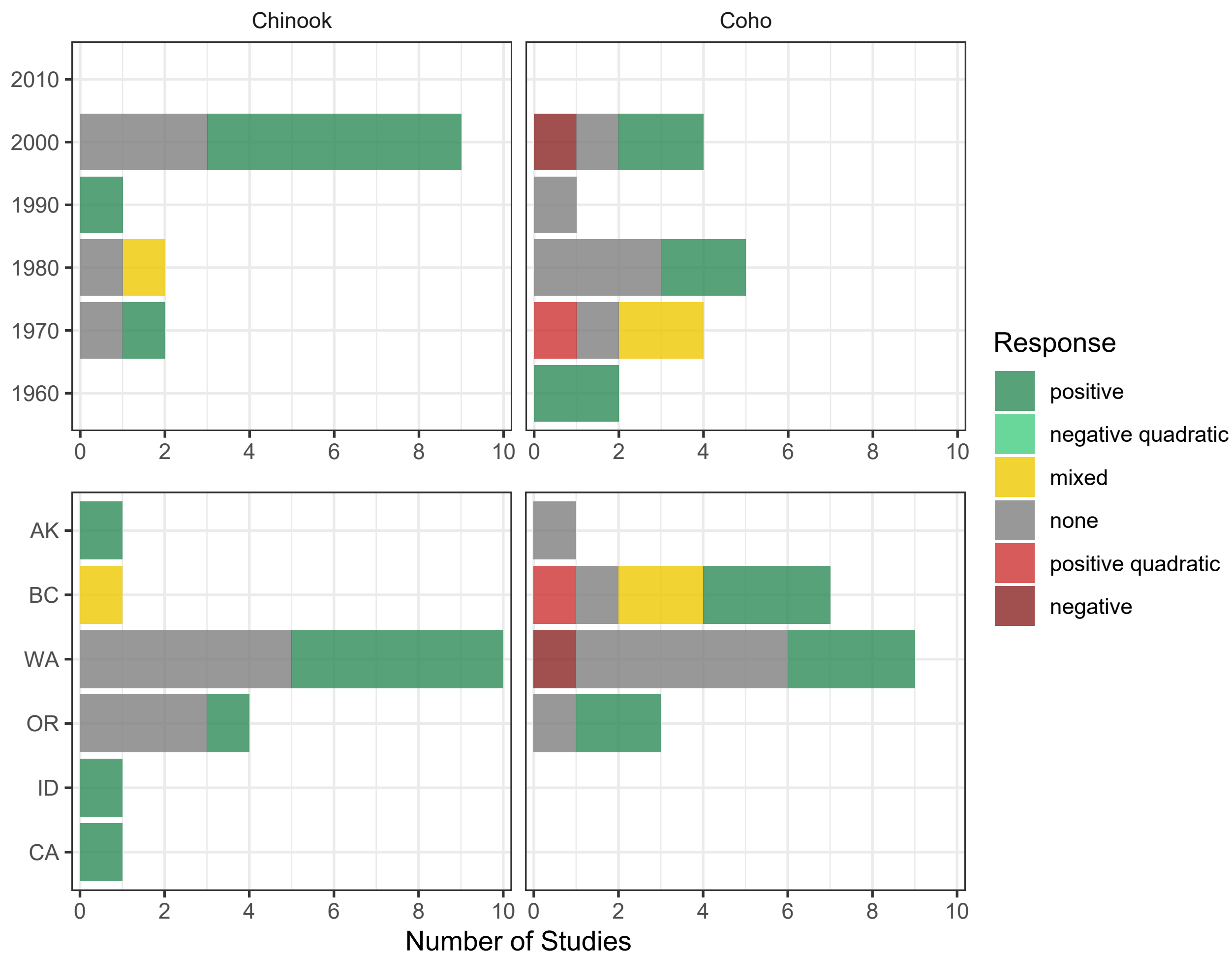


**Figure 7:** Number of studies on the effects of increased size at release on survival of Chinook (left) and Coho (right) by decade (top) and region (bottom). Colours represent the nature of the survival response. Multi-decadal studies have been excluded from the top panels and cross-regional studies have been excluded from the bottom panel.

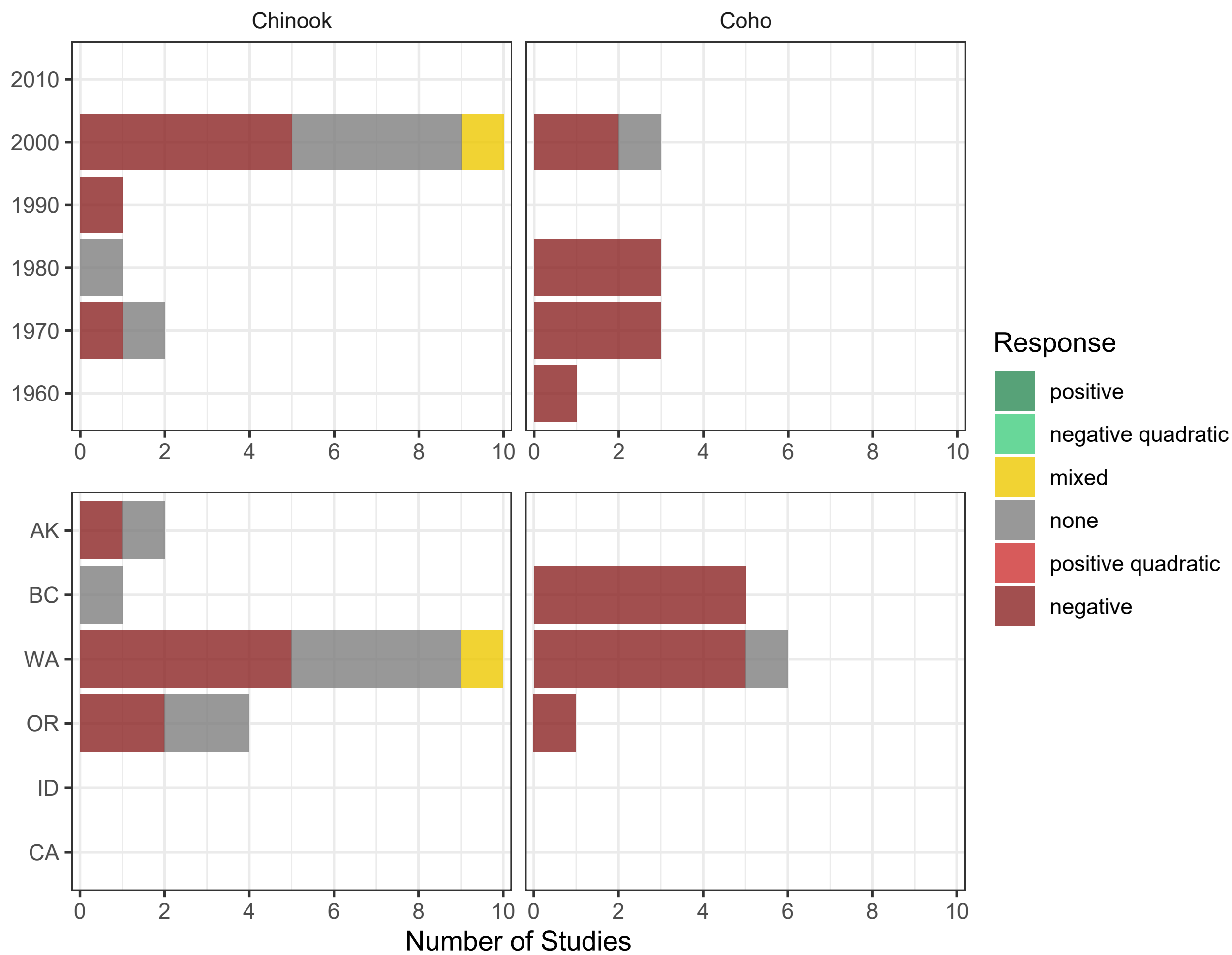


**Figure 8:** Number of studies on the effects of increased size at release on return age of Chinook (left) and Coho (right) by decade (top) and region (bottom). Colours represent the nature of the survival response. Multi-decadal studies have been excluded from the top panels and cross-regional studies have been excluded from the bottom panel.

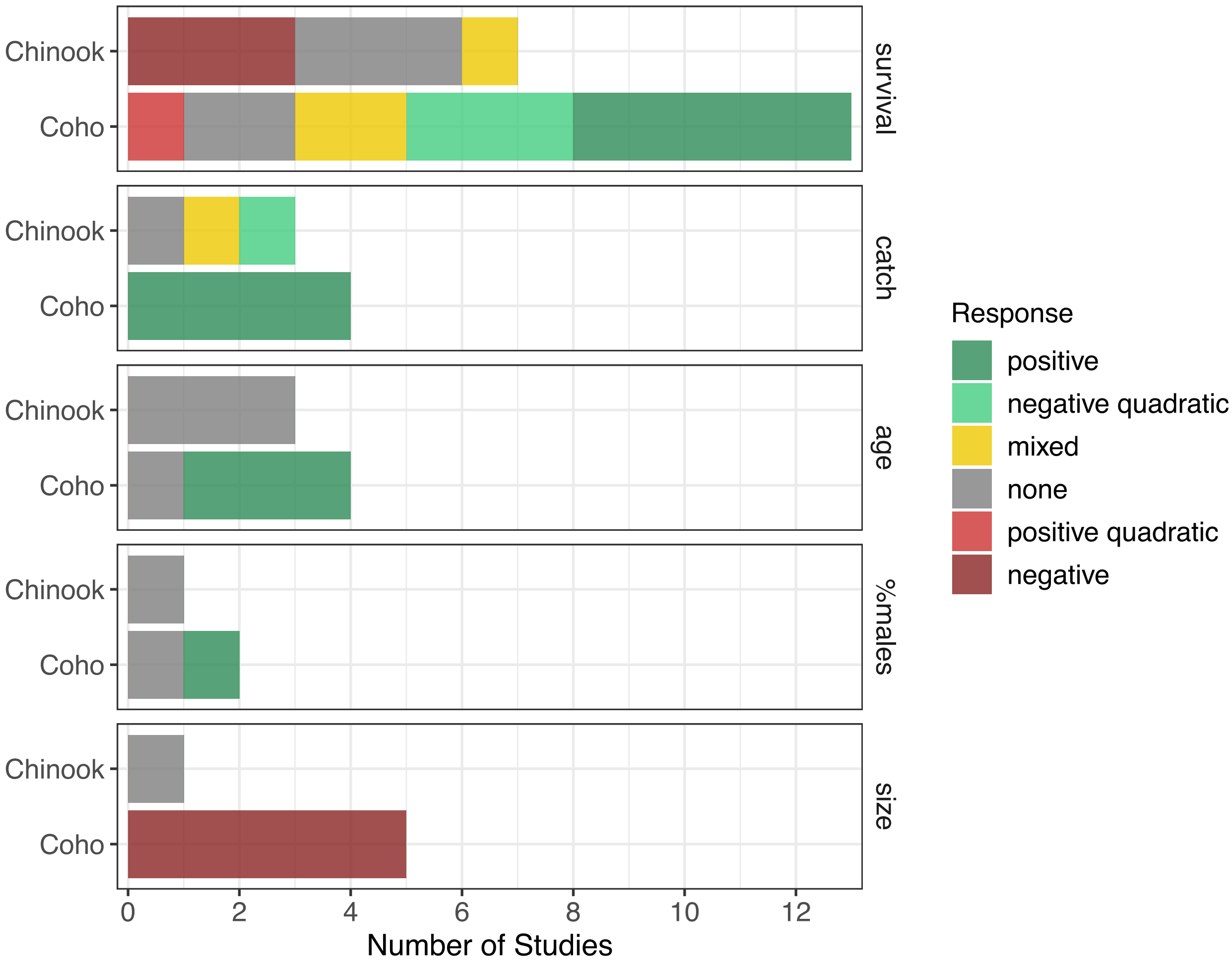


**Figure 9:** Summary of the effects of a later release on survival, catch, age at return, proportion of males in returns, and size at return for Chinook and Coho and the number of studies reporting each relationship in the literature.

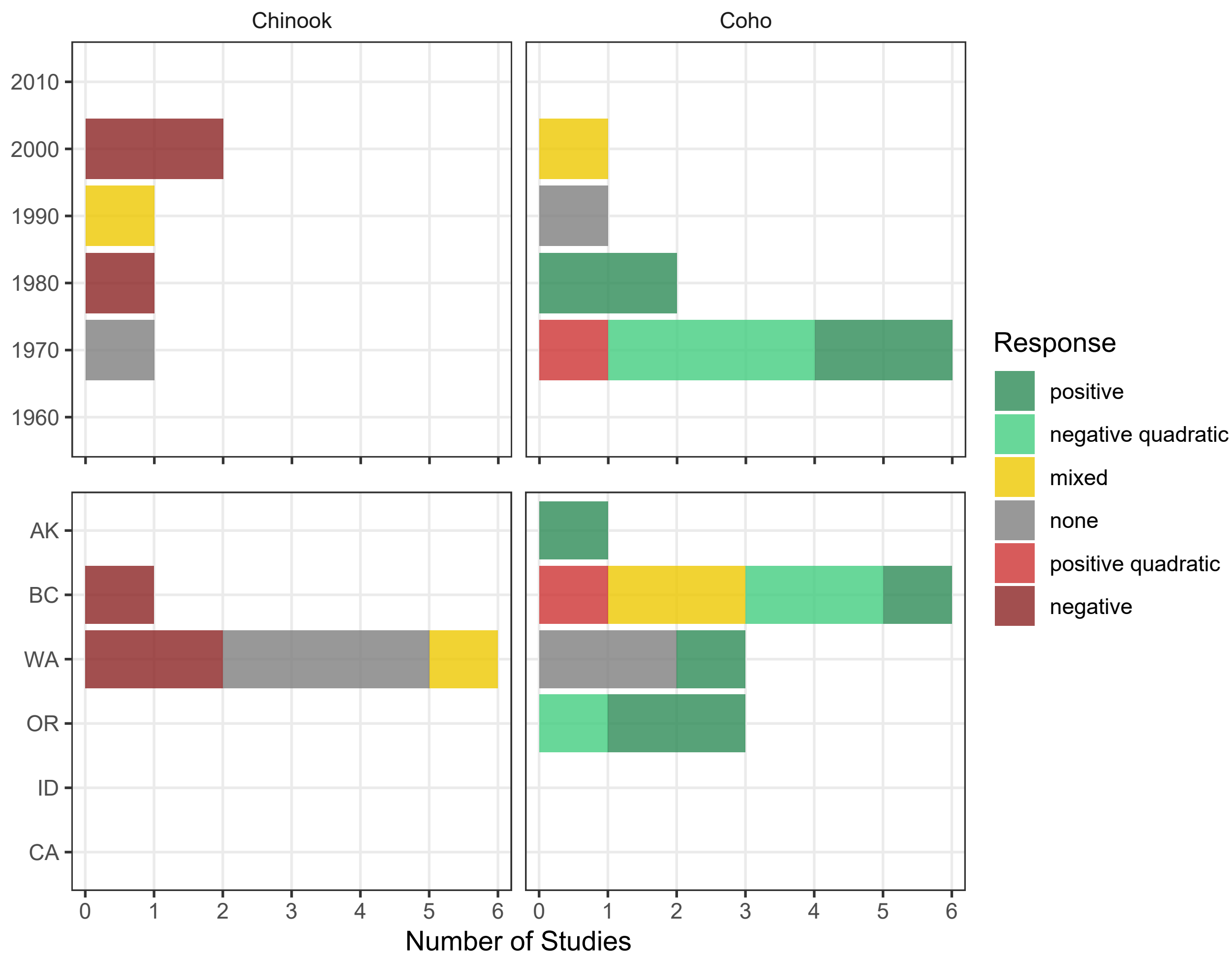


**Figure 10:** The effects of a later release on survival of Chinook (left) and Coho (right) by decade (top) and region (bottom) and the number of studies reporting each relationship in the literature. Colours represent the nature of the survival response. Multi-decadal studies have been excluded from the top panels and cross-regional studies have been excluded from the bottom panel.

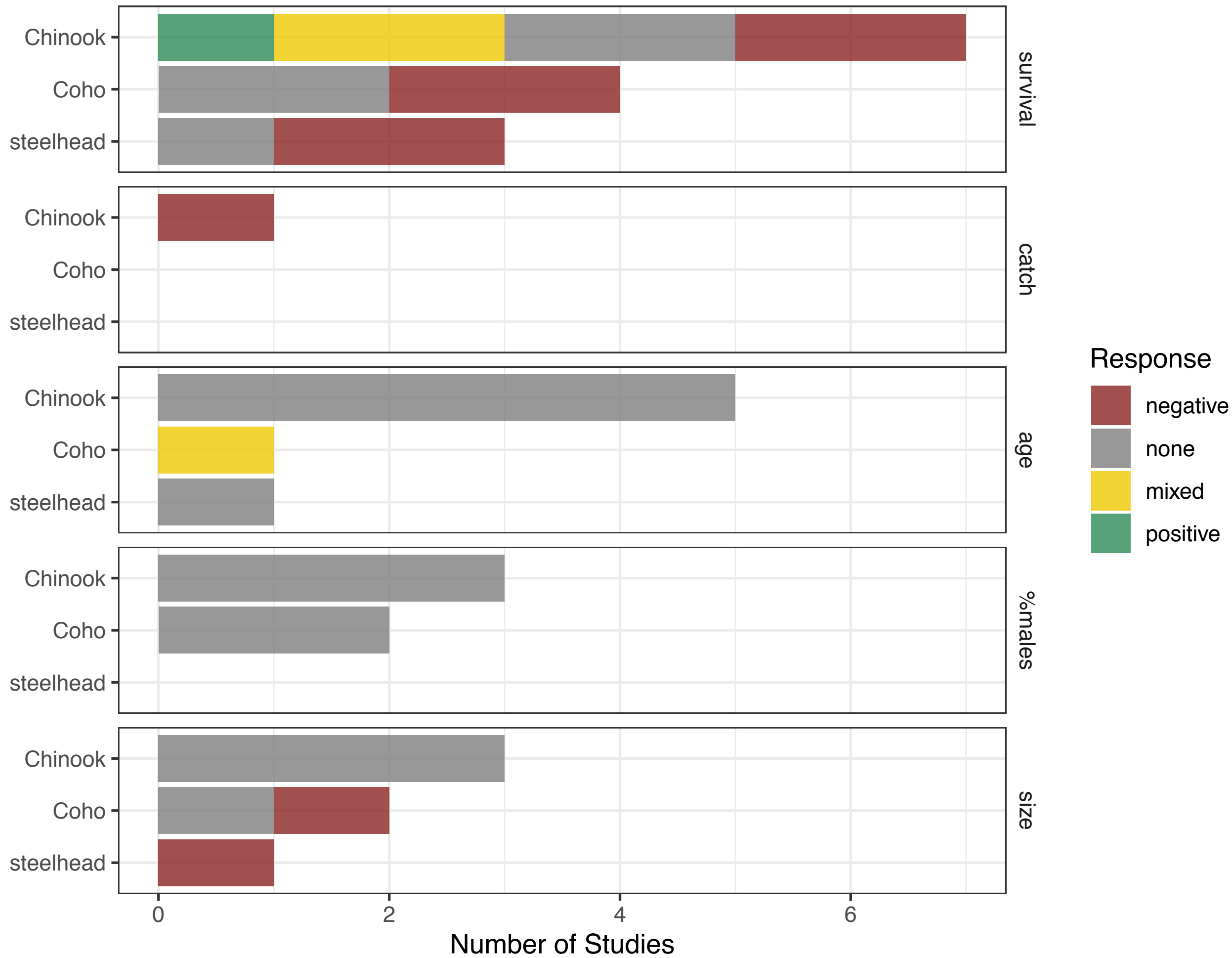


**Figure 11:** Summary of results in the literature on the relationship between rearing densities and response variables survival, catch, age, % males, and adult size for Chinook, Coho, and steelhead.

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Photo by: Sam James

# APPENDIX

## Hatchery Release Strategies Literature Search: December 12, 2019

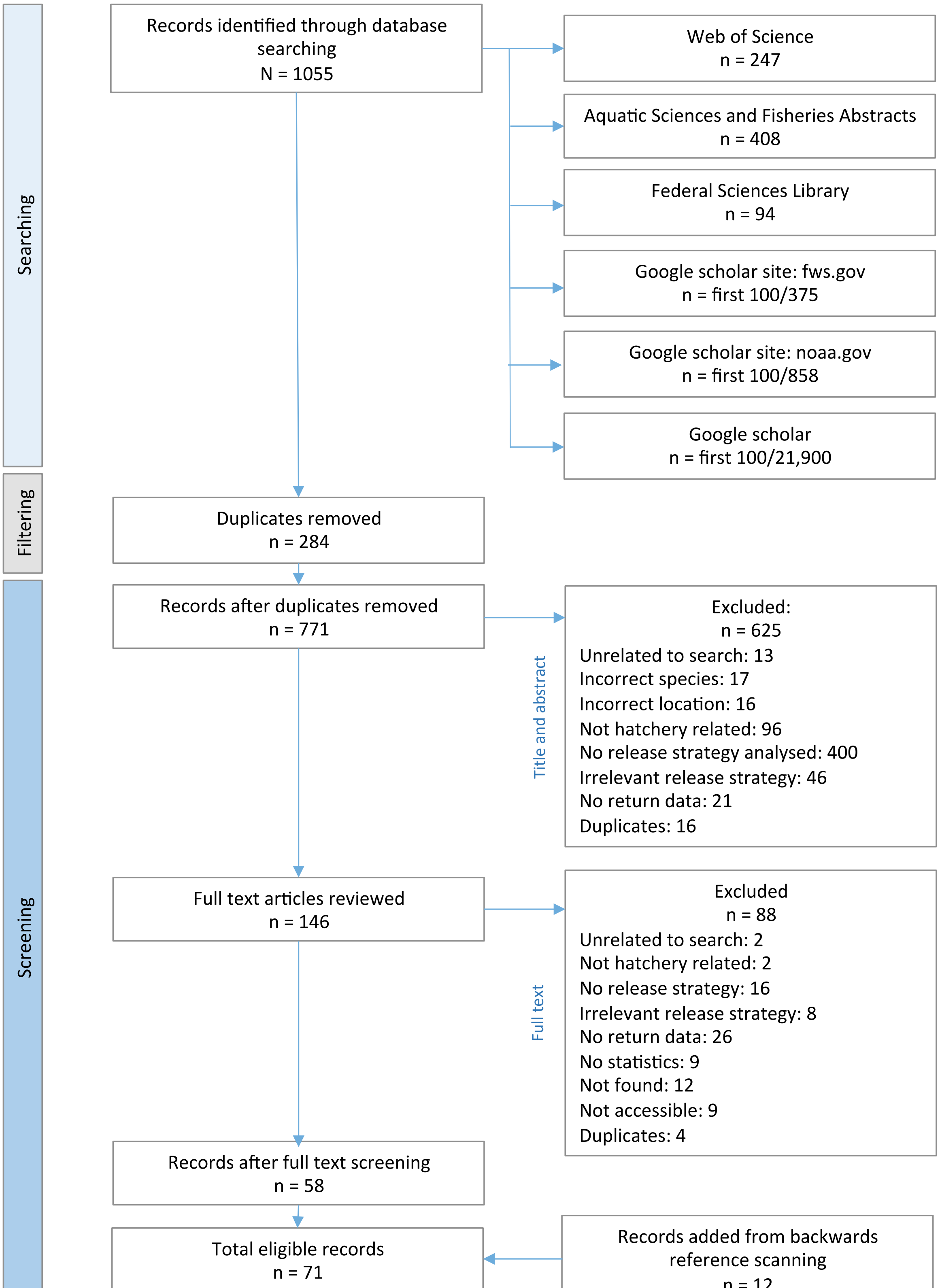


**Figure A2:** Systematic literature review flow diagram of the updated search and screening process conducted on January 5, 2021.

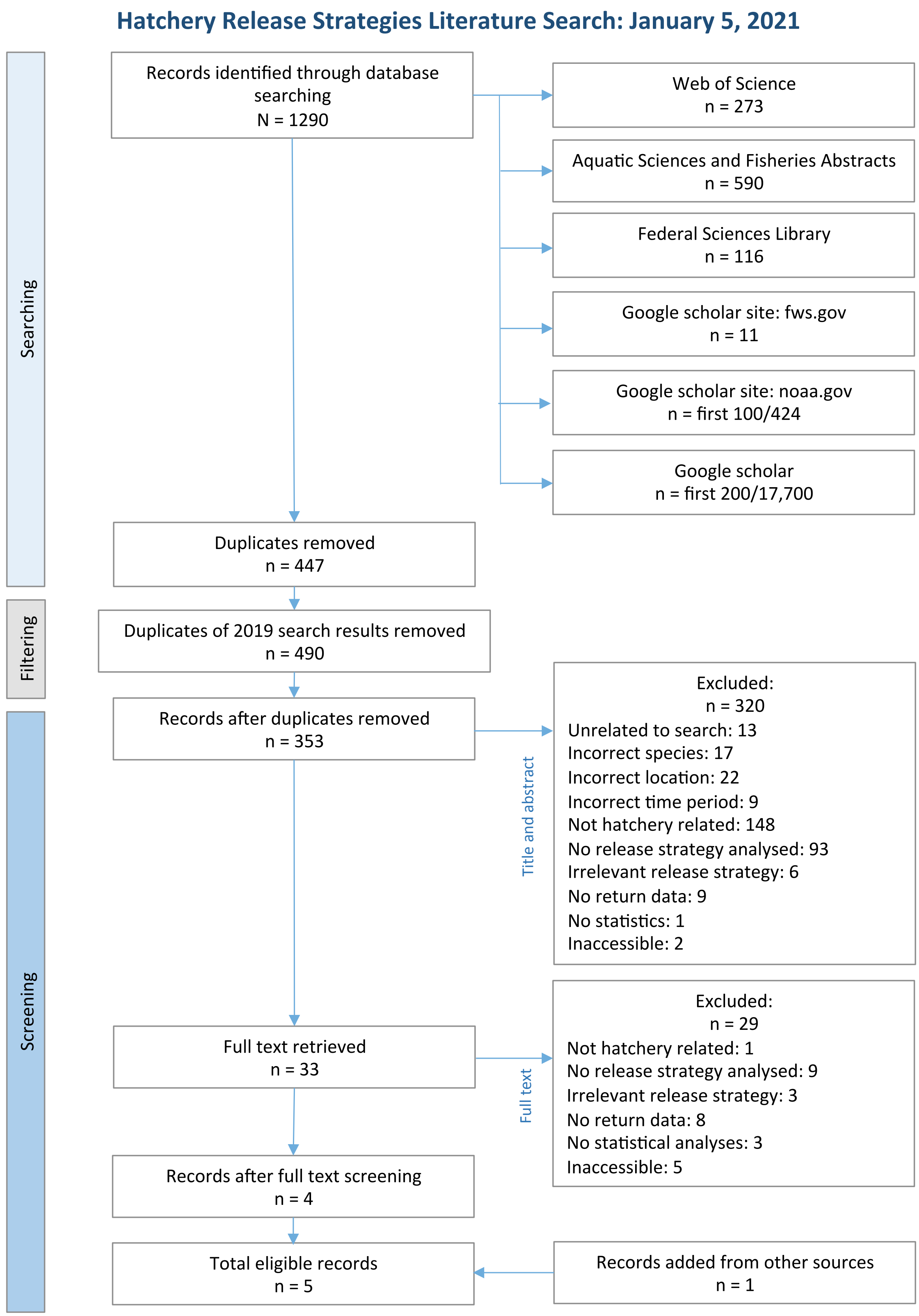


**Figure A2:** Systematic literature review flow diagram of the updated search and screening process conducted on January 5, 2021.


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