PACIFIC SALMON
FOUNDATION

HATCHERY-WILD INTERACTIONS SYSTEMATIC LITERATURE REVIEW

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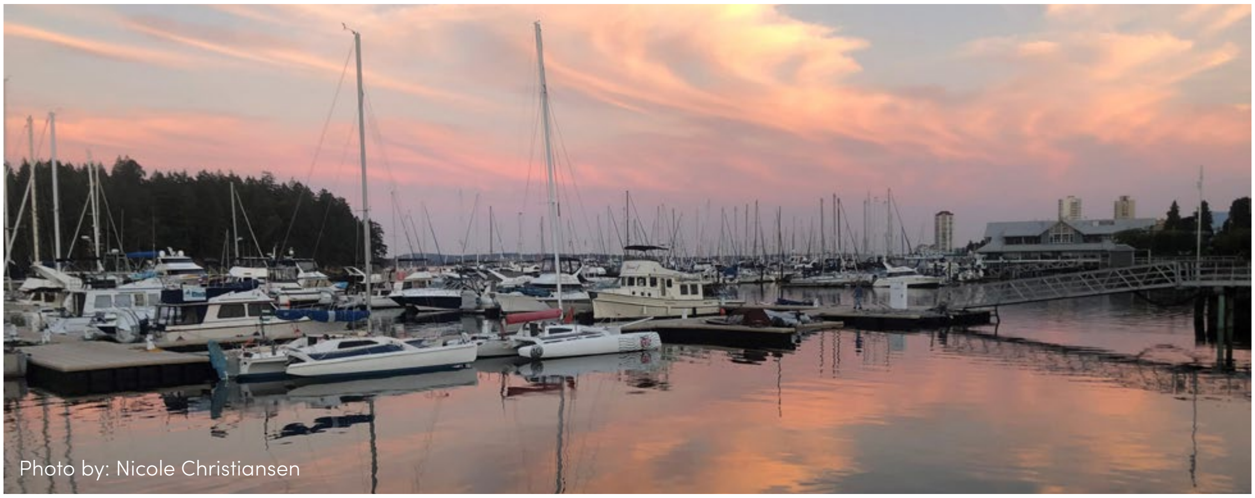
Photo by: Nicole Christiansen

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Cover photos by: top and left, Eiko Jones; centre, D. Swainson and right, Nicole Christiansen

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Photo by: Eiko Jones

EXECUTIVE SUMMARY

As a part of the Pacific Salmon Foundation's comprehensive review of hatchery effectiveness in British Columbia, a systematic literature review has been carried out to provide a clear picture of the current state of knowledge concerning the **interactions between wild and hatchery-origin Pacific salmon**. The goal of our review was to address the following questions:

1. **What is the current state of knowledge on interactions between hatchery-origin and wild salmon?**
2. **What are the major types of interactions? How do the studies and interactions vary geographically, and across species?**
3. **What recommendations are made in the literature to mitigate effects of these interactions?**
4. **What are the major areas of research still needed?**

After a search and screening process designed to be unbiased and extensive, an initial list of 4974 publications was screened down to a total of 112 relevant studies and literature reviews directly addressing interactions between wild and hatchery-origin salmon (with 85 of those suitable for analysis). The studies were categorized based on the nature of the interaction between hatchery-origin and wild fish that was explored and then assessed as to whether that interaction was positive, negative, or had no effect. The categories were: genetics, competition, population mixing, fish heath, and outcomes based studies.

The majority of studies (50, including 7 literature reviews) found a negative effect of hatchery fish interactions with wild fish, whereas only two studies demonstrated a positive effect and 33 studies had no reported effects. The most studied category of interaction was genetics, the most studied species was Chinook, and the majority of studies were carried out in the United States.

In most studies, authors provided recommendations to mitigate or eliminate the negative consequences of hatchery-wild interactions. The main themes of the recommendations include limiting the interactions from ever occurring; implementing best practices in hatcheries; refocusing the priorities and approach of hatcheries towards limiting interactions; using adaptive management practices; and weighing external factors such as environmental degradation, climate change, and social and cultural concerns.

Across the literature surveyed for this review, the body of scientific evidence reveals that hatcheries can harm wild salmon. Continuing to identify, study, and mitigate hatchery-wild interactions will help to secure the continued survival of Pacific salmon for future generations and enable hatchery programs to potentially augment natural production of Pacific salmon.

Photo by: Ben Fortini

INTRODUCTION

Hatcheries are fish production facilities that rear fish in captivity and then release them into the wild. They have been used to produce Atlantic (*Salmo salar*) and Pacific salmon (*Oncorhyncus* spp.) across the world since the late 19th century. Modern-day enhancement[1] in British Columbia began in earnest in 1977 with the creation of the Salmonid Enhancement Program (SEP 2013; MacKinlay et al. 2004). Due to their popularity as a food source and their anadromous life history, salmon have long been identified as excellent candidates for enhancement (Gardner et al. 2004). Enhancement is not only performed to boost the harvest of salmon for fisheries, but also to maintain or rebuild struggling wild stocks that may not be able to sustain themselves if left unenhanced. It is important to note that hatchery programs with these differing goals will naturally present different challenges, and to recognize that not every hatchery is the same. The objectives and operations of a hatchery can be significantly different, and as such, the findings around risks and benefits cannot be applied as blanket conclusions about all hatcheries. To fully understand the positive and negative effects or risks of any specific hatchery, the operations and outcomes from that specific operation need to be taken into consideration and assessed. However, while the specific risks and benefits may be different for an enhancement program being carried out with harvest objectives compared to one with rebuilding objectives, the central issue of the nature and severity of interactions with salmon in their natural habitats remains.

There have been considerable scientific concerns towards hatcheries for a long time with calls for the curtailing or outright cessation of enhancement of Pacific salmon coming thirty years ago (Waples 1991, Hilborn 1992). This unease arose from ongoing declines of many Pacific salmon stocks despite increasing hatchery releases, calling into doubt the foundational vision of hatcheries as a tool for producing abundant harvests (Gardner et al. 2004). Additionally, developments in genetic techniques, along with increased attention to the ecological consequences of human actions in the environment, led to questions about what effects these hatchery releases might be having on the naturally spawning stocks of salmon sharing the same habitats. The use of hatcheries to address the ongoing decline of wild salmon populations has been deemed by some as an over-reliance on technology to solve a problem that could otherwise be mitigated by attempts to support and strengthen wild salmon in other ways (Meffe 1992, Claussen & Philipp 2022).

Negative effects of hatchery-origin Pacific salmon on their wild counterparts are an important consideration in the overall risk-benefit calculation of enhancement, which will also depend on the goals of the hatchery release program. Indeed, if these effects are sufficiently negative, they may outweigh any increases in productivity and catch resulting from hatchery releases, since negative impacts would imply harm to wild stocks. These risks are known and many hatchery managers already seek to mitigate them. For instance, SEP's Biological Risk Management Framework serves to outline Canada's approach to managing these potential negative interactions (SEP 2013).

It is important to note that hatcheries are not the only factor potentially contributing to the overall decline of Pacific salmon. Overharvesting of fish, habitat degradation and destruction, hydroelectric installations, pollution, sea-pen aquaculture, and climate change are all important stressors (Gardner et al. 2004). The magnitude of the risks posed by both hatcheries and interactions with these other effects are difficult to quantify, and it is therefore extremely important to take stock of what has been learned in order to direct future research in this area.

Given the above concerns and gaps in knowledge, we conducted a systematic review of the literature to establish the current state of knowledge on hatchery-wild interactions. While reviews of this nature have been performed in the past, it has been over a decade since the last major publication (Naish et al. 2008). The goal of our review was to address the following questions:

1. **What is the current state of knowledge on interactions between hatchery-origin and wild salmon?**
2. **What are the major types of interactions? How do the studies and interactions vary geographically, and across species?**
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4. **What are the major areas of research still needed?**

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1. Modern enhancement programs are broader than just hatchery culture, but in this review, only the interaction of hatchery produced salmon with salmon produced in their natural habitats is assessed.

METHODS

In the interest of summarizing the existing literature in an unbiased and repeatable way, a list of key references was derived from the literature. Search terms were selected to identify key references and a series of searches of key scientific databases performed. Results of the searches were individually screened for relevance. Those studies chosen for inclusion in the review were categorized by interaction type as well as effect direction, to provide an overall determination of the weight of evidence concerning hatchery-wild interactions with Pacific salmon.

SCOPE OF THE REVIEW

The scope of the review was broad, including studies of both Atlantic (*Salmo salar*) and Pacific (*Oncorynchus* spp.) salmon, from all regions of the world where these species are enhanced, North America, Europe, and Asia. Any study or publication detailing interactions of any type between wild-origin salmon and hatchery-origin salmon were sought for inclusion in the review.

SEARCH

Searches were conducted in May of 2021. Searches were carried out using search terms based on the initial list of key references. The search terms and the key reference list are available in the supplementary materials (Appendix 1). While the terms had to be adapted to each database following the flexibility of the search engine, the overall format of the search terms included four components. First, studies had to involve one or more salmon species, either Pacific or Atlantic. The second and third components required some mention of hatchery origin and wild origin. Finally, some interaction between the two different types of fish was an essential component. No date of publication restrictions was placed on the search criteria, however, all studies included within the review were between 1986 and 2021.

Four databases were searched using these terms: Web of Science, ASFA (Aquatic Sciences and Fisheries Abstracts), DFO Waves, and Google Scholar. All results of the search were taken from the first three databases, while the first 200 results were taken from Google Scholar, which returned over a million results. The combined list of results (n=7805) was imported into Covidence, a software package for systematic literature reviews, for removal of duplicates. After deduplication in Covidence, several duplicates remained and were removed manually, resulting in the final pool of unique references (n=4974).

SCREENING

The titles and abstracts of the remaining references were screened for eligibility. The search terms served as the main criteria used to screen studies for inclusion in this review. Any publication that included an interaction between wild and hatchery salmon was included. Common types of studies that were excluded concerned aquaculture and sea-pen escapees, rather than hatchery-origin fish, as well as analyses of biological traits and how they differed between hatchery-origin and wild-origin fish without any interaction element.

To refine the inclusion criteria and the overall screening process, a random selection of 500 references, approximately 10% of the search results, were screened in parallel by two separate individuals. This process was carried out to ensure there was limited bias in the screening process and strengthened the selection criteria. While both screeners included most of the same papers, the main difference centered on the aforementioned ‘biological trait’ studies, which included both hatchery and wild salmon but did not study an interaction.

After screening of the search results, slightly more than 2 percent of references were chosen for inclusion in the review (n=107). However, five of the studies contained separate analyses in different subtypes, and therefore each analysis was considered separately. Therefore, the final number of studies for analysis was 112. Within this total were 73 experimental and 5 simulation studies, 27 literature reviews, 3 opinion pieces, 2 case studies, 1 workshop proceeding, and 1 ethnographic interview. A number of the literature reviews (20), the opinion, case studies, workshop, and interview documents were too broad in scope to be categorized into an interaction type or summarized into a directional conclusion for the weight of evidence analysis. The contribution of these broader works to this review was to incorporate and consider the recommendations made within them for the discussion section, as well as to verify that all relevant studies were included. The total final number of studies that were applicable for analysis in this review was 85. See Appendix 2 for summary table of screened results.

ANALYSIS

Due to a wide diversity of methods utilized between studies, a weight of evidence approach was employed to develop an overall impression of the common conclusions across these studies. The weight of evidence approach sought to answer the main question of the review by asking how many of the included references from the literature found a positive effect resulting from hatchery-wild interactions and comparing that number to the number of studies finding a negative effect. Studies could also be categorized as finding no effect, if statistical significance of an effect was not found. It is important to note that studies that found no effect may have had limitations related to sample size, methodology, or study design that resulted in a lack of power to identify effects. However, comparing the results in this way still provides an indication of the state of our knowledge concerning hatchery-wild interactions.

CATEGORIZATION

The interactions between hatchery-origin and wild fish found in this review were apportioned into the following categories similar to previous reviews (Naish et al. 2008, SEP 2013):

1. **Genetics**
2. **Competition**
3. **Population mixing**
4. **Fish health**
5. **Outcomes-based studies**

Categories 1-4 include studies that look at a particular interaction and/or its immediate effect. The fifth category includes studies that look at a specific outcome for wild salmon populations. Outcomes-based studies are an important piece of the overall picture because, while they do not specifically identify the nature of the interaction, they look for downstream consequences such as reduced survival or productivity of wild salmon. This complements the studies found in the other four categories, which often seek evidence of an interaction but can only speculate as to its ultimate consequences (Figure 1).

Figure 1. Flow chart depicting the relationship between interaction, the effect it has and the ultimate outcome. Categories 1-4 focus on the relationship between interaction and immediate effects, while Category 5 studies do not identify the immediate effect but investigate for the eventual outcomes or meaningful consequences.

Photo by: Nicole Christiansen

For each category, the references are also broken into subtypes, providing a further organization of the studies into more specific types of interaction.

For genetics, the subtypes used are:

A. **Domestication**, where hatcheries inadvertently select for traits in the broodstock collection or rearing processes that favor performance in the hatchery, rather than the wild, leading to propagation of these domesticated genes in wild fish;

B. **Epigenetics**, where the hatchery rearing process results in a developmental imprint on fish before release, such that traits favoured in the hatchery may be passed on to wild fish;

C. **Loss of genetic diversity**, where through various means hatchery-origin fish reduce the diversity in the conspecific wild population;

D. **Reduction of effective population size**, where despite increases in abundance in some cases, the actual breeding population is reduced; and

E. **Reduction of fitness**, where non-adaptive genes are passed into the wild population from hatchery-origin fish.

For competition, the subtypes used are:

A. **Direct competition**, where hatchery-origin and wild salmon compete for a resource, such as food;

B. **Displacement**, where wild fish leave habitat as a result of hatchery-origin fish; and

C. **Predation**, where hatchery-origin fish consume wild fish or attract predators.

For population mixing the subtypes used are:

A. **Replacement**, where hatchery-origin fish replace, rather than supplement, wild fish; and

B. **Straying**, where hatchery-origin fish spawn among wild fish in neighboring, unenhanced waters.

For fish health, the subtypes used are:

A. **Disease spread**, where infected hatchery salmon are released and transmit pathogens to wild fish; and

B. **Vaccination**, where hatchery releases are used to fight an outbreak in a wild population.

For outcomes-based studies, the subtypes used are:

A. **Productivity**, where the outcome is the number of recruits per spawner;

B. **Size at return**, where the outcome is the physical size of salmon returning to spawn; and

C. **Survival**, where the outcome of concern is the survival of wild fish.

Photo by: Collin Middleton

RESULTS

The most commonly studied category was genetics (n=27), followed by outcomes-based effects (n=21), competition (n=20), fishery mixing (n=12), and fish health (n=5), with a final portion of studies not falling into the described categories (n=27) because they were too broad in scope as discussed in Screening section of Methods (Figure 2).

Most studies were performed on Chinook (n=21), followed by steelhead (n=17), with Atlantic (n=9), coho (n=7), chum (n=6), pink (n=4), masu (n=3), and sockeye (n=2) (Figure 3). A number of studies involved multiple species (n=16) (Figure 3).

Most study areas were located in the United States (n=58), followed by ecosystem-scale studies that did not focus on a particular region, such as literature reviews (Figure 4). Smaller numbers of studies were from Canada (n=13), Europe (n=9), and Asia (n=6). A number of studies, often reviews, were considered ecosystem-scale due to not being related to a specific geographic region (n=19). Studies performed in controlled conditions rather than nature, along with simulations, were not assigned a study area and categorized as n/a (n=7).

For interactions between hatchery and wild salmon overall (n=85), there were 50 conclusions of negative effects, 30 no effect (Figure 5) and two that had a positive effect.

For the genetics studies (n=27), there were 17 studies finding a negative effect, nine finding no effect, and a single study finding a positive effect (Figure 6). Within subtypes, studies concerning domestication (n=5), and epigenetics (n=1) all found negative effects. For studies of fitness (n=6), all but one, which reported no effect, were considered to have negative effects. Of the studies of genetic diversity (n=11), four studies show negative effects, six showed no effects and one study showed positive effects. Studies of reductions to effective population size (n=4) were split evenly between negative and no effect.

In the competition category (n=20), there were nine studies that found a negative effect, 11 studies found no effect, and none that reported a positive effect (Figure 7). Within subtypes, direct competition was evenly split between negative and no effect, and displacement showed a no effect result. The single predation study found a negative effect.

All studies that looked at fishery mixing studies (n=12) showed a negative effect (Figure 8).

For fish health (n=5), four of the studies showed no effect, and a single study found a negative effect (Figure 9). This pattern is also the same within the disease spread subtype, which includes all but one study: the single vaccination study that finds a (potentially) positive effect.

In outcomes-based effects studies (n=21), there were 11 studies that showed a negative effect, and 10 that showed no effect. (Figure 10). The single size at return study found a negative effect.

Photo by: D. Swainson

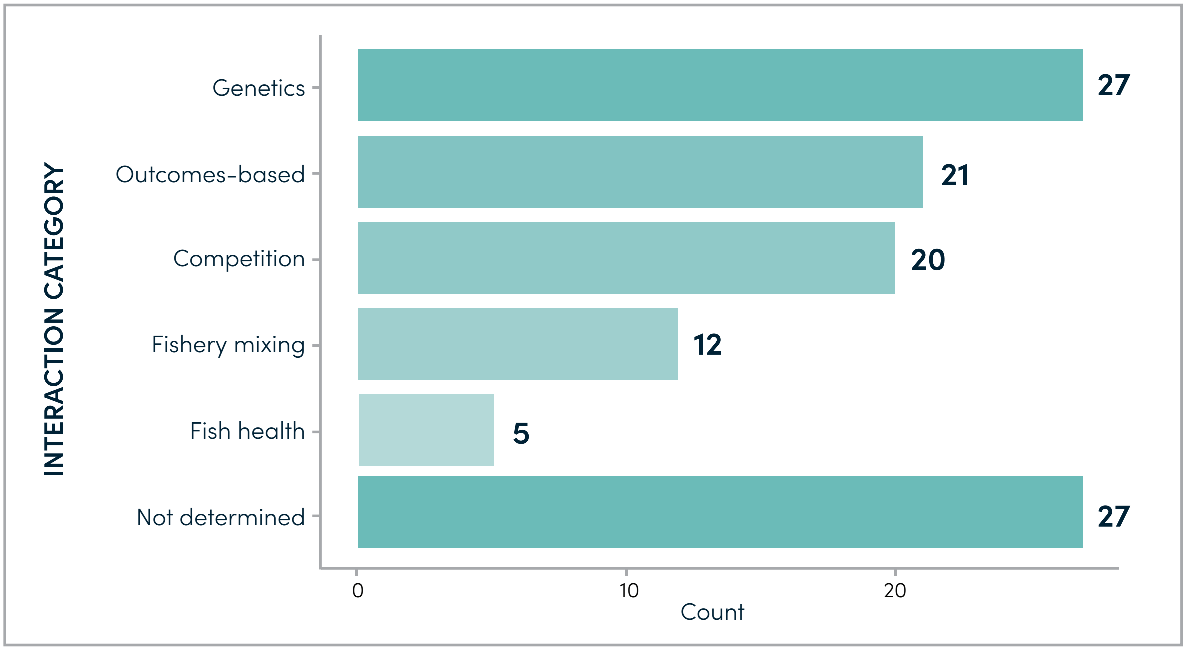

Figure 2. Number of studies in each category.

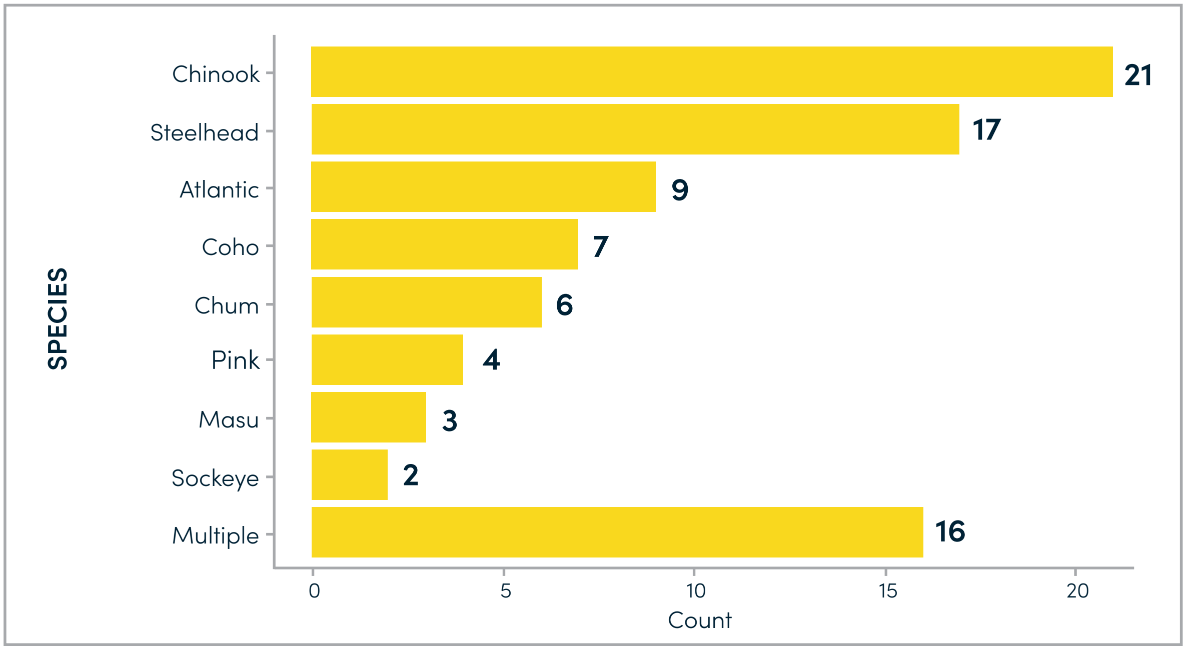

Figure 3. The number of studies involving each species.

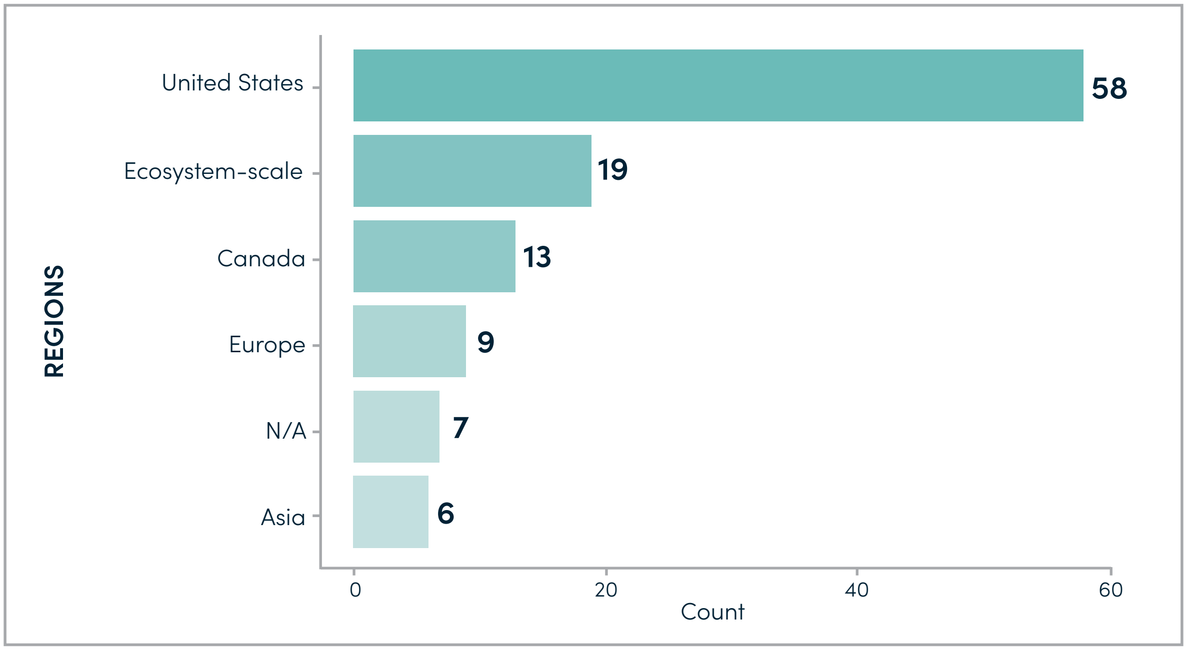

Figure 4. The number of studies performed on data from each region. Ecosystem-scale refers to studies that did not look at a particular region, such as literature reviews. n/a refers to studies that were performed in controlled conditions, or simulations.

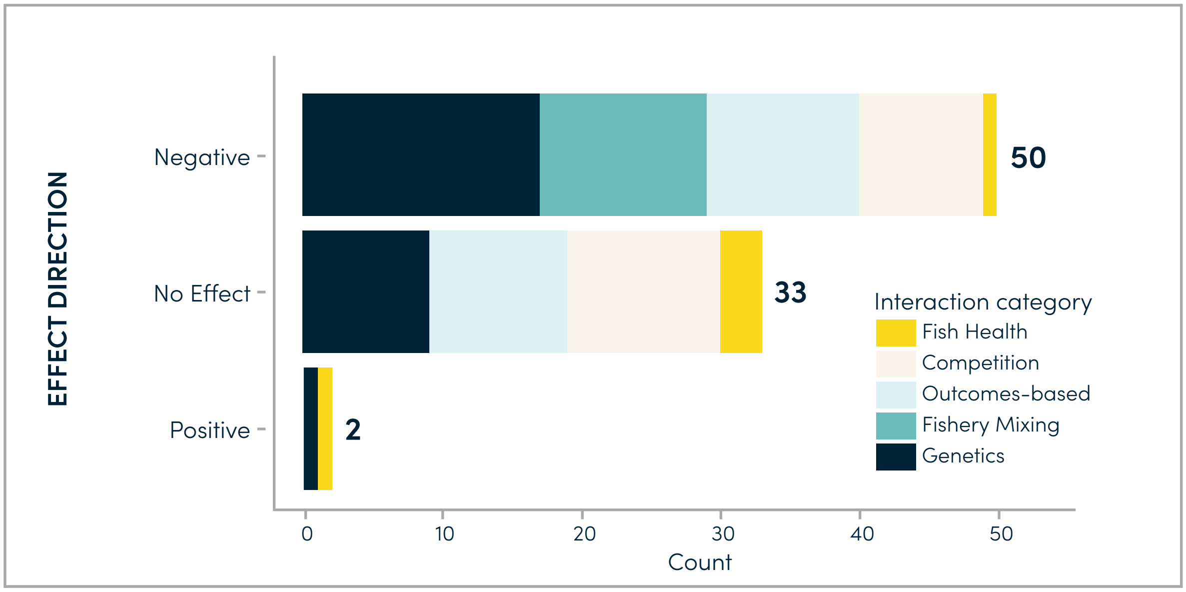

Figure 5. The number of studies showing a negative effect, no effect, or a positive effect for each interaction category.

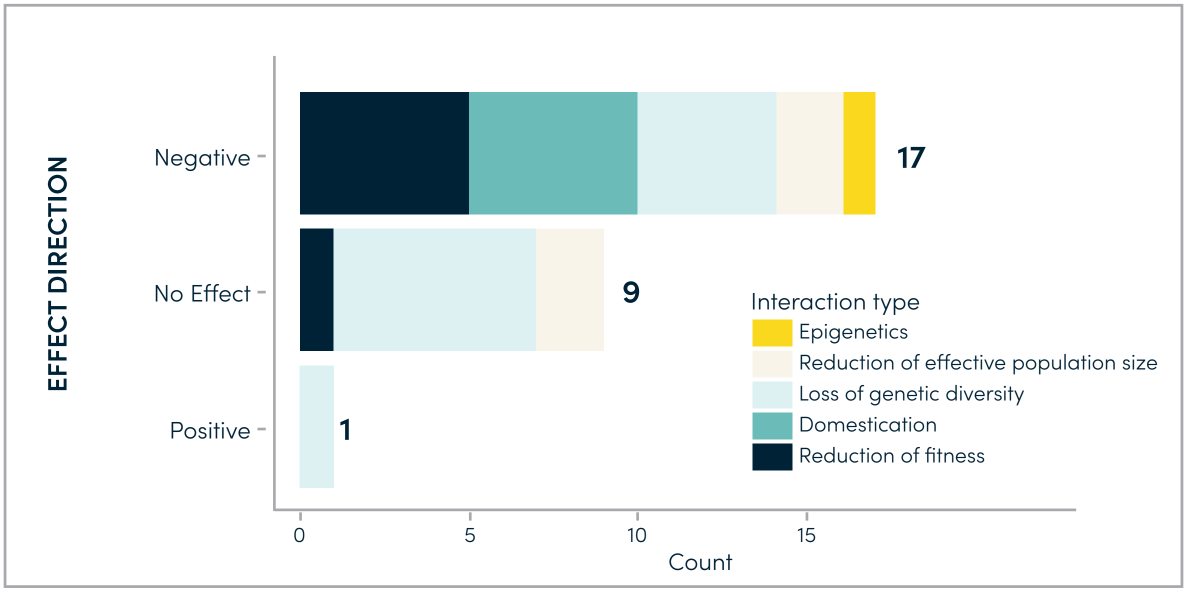

Figure 6. The number of genetics studies showing a negative effect, no effect, or a positive effect for each interaction subtype.

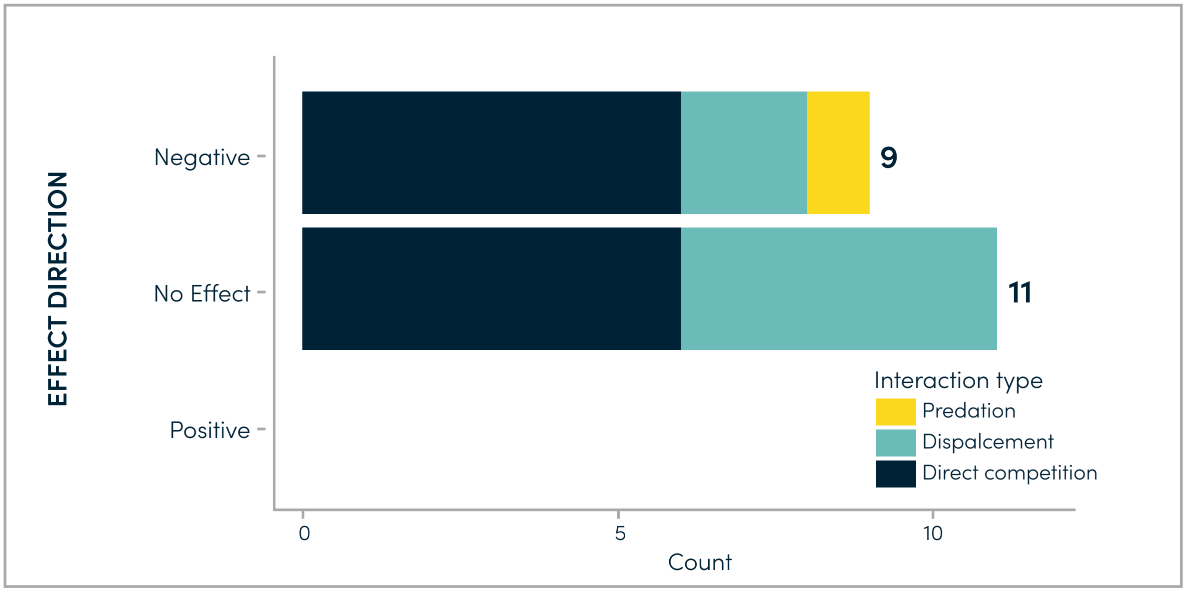

Figure 7. The number of competition studies showing a negative effect, no effect, or a positive effect for each interaction subtype.

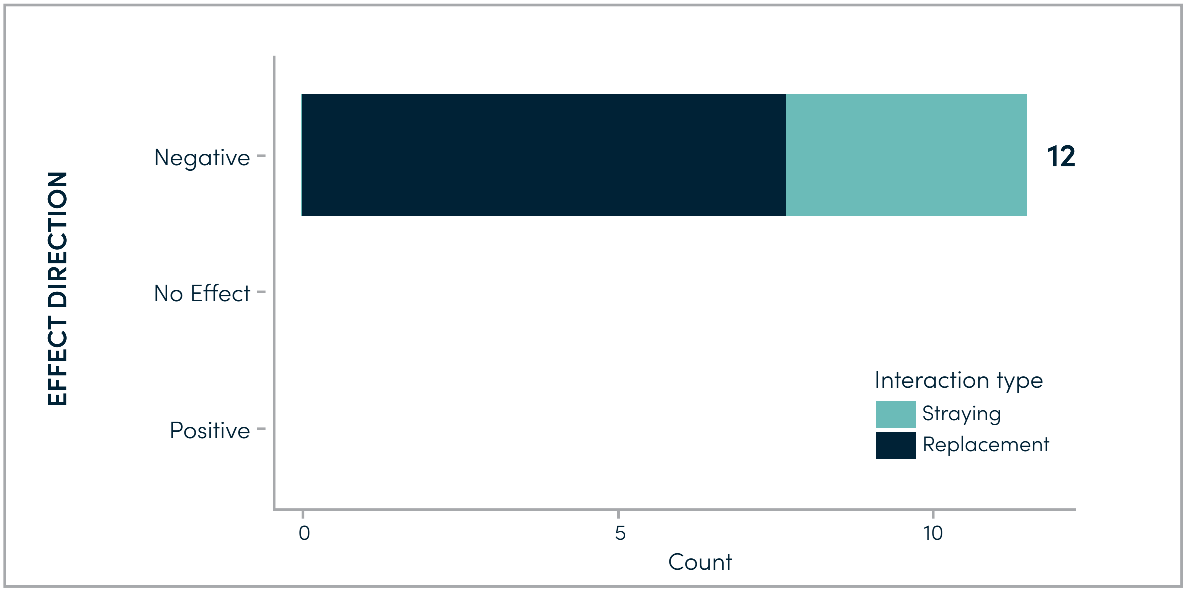

Figure 8. The number of fishery mixing studies showing a negative effect, no effect, or a positive effect for each interaction subtype.

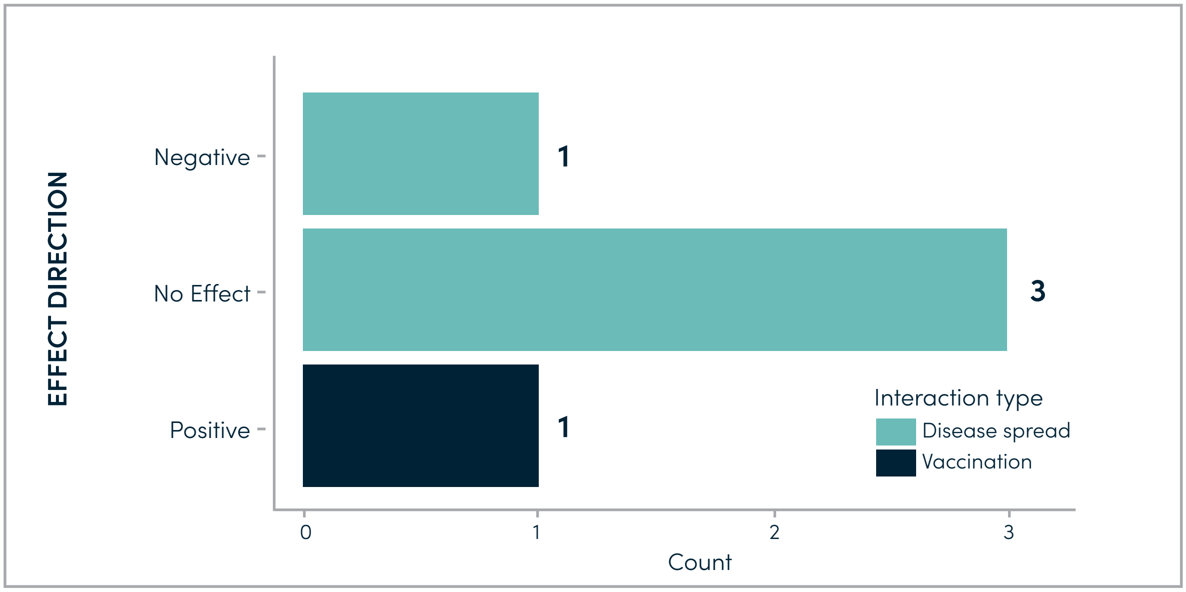

Figure 9. The number of competition studies showing a negative effect, no effect, or a positive effect for each interaction subtype.

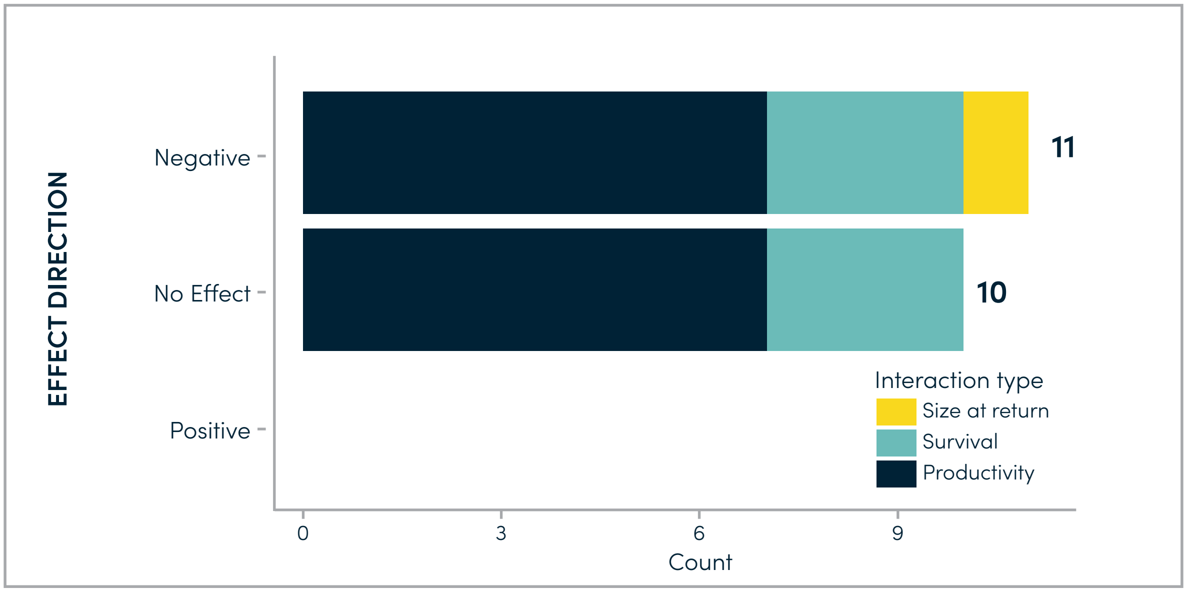

Figure 10. The number of outcome-based effects studies showing a negative effect or no effect, for each interaction subtype.


Photo by: Ben Fortini

LITERATURE SUMMARY

This section summarizes the findings of the studies included in the review, such as important results and takeaways from each, organized by subtype. Within each section, studies are separated by effect direction from the weight of evidence analysis.

GENETICS

Domestication

All reviewed studies of domestication selection found a negative effect of hatchery fish on wild fish. In reviews of Atlantic salmon culture in Europe, it was noted that if intentional steps to prevent domestication selection are not taken, fish at release will have been optimized for survival in hatchery conditions, and not in the wild (Thorpe 1991, Heggberget et al. 1993). This has the potential to be counter-productive for both harvest and conservation goals since domesticated hatchery-origin fish are frequently reported to be less likely to survive. Additionally, the genetics associated with domestication could be introduced into the wild population. In Pacific salmon, data pooled from several studies provided strong evidence for the introduction of domesticated traits into wild populations of salmon from hatchery-origin fish (Reisenbichler & Rubin 1999). Once these domesticated genotypes exist in the wild population, further hatchery releases only serve to increase their prevalence (Hagen et al. 1999). This is because domesticated fish captured as broodstock will be more successful in the hatchery, resulting in a feedback loop. Measures taken in an attempt to reduce hatchery-wild interactions can also unintentionally cause domestication selection (Austin et al. 2021). In this study, the authors found that the mean spawning time of a wild Chinook population was moving earlier into the year, despite overall trends in wild populations moving in the opposite direction due to climate change. The hatchery population had been intentionally released earlier to avoid interaction with wild conspecifics, ultimately causing genetic changes to phenology that introgress into those wild fish.

Epigenetics

The single study of epigenetics suggested that a mechanism for rapid negative consequences of the introgression of hatchery strays into wild populations could be due to epigenetic changes (Barreto et al. 2019). Indeed, a single generation of hatchery rearing was found to introduce DNA methylation changes, some of which were passed onto offspring that were never reared in hatchery conditions.

Loss of genetic diversity

Four out of 11 studies concerning losses in genetic diversity found a negative effect on wild fish. A review of hatchery practices and outcomes in the Soviet Union found that supplementation with little concern for using local broodstock or preserving wild populations led to losses in genetic diversity of wild salmon (Altukhov & Salmenkova 1991). A review of Atlantic salmon supplementation highlighted the particular significance of genetic interactions between hatchery and wild salmon (Youngson & Verspoor 1998). This was due to losses in genetic diversity making the wild population less viable in the present and into the future due to inbreeding and a weakened ability to adapt to changing conditions. Losses in genetic diversity of a wild steelhead population due to hatchery releases persisted even after the cessation of the supplementation program (Johnson et al. 2021). While sourcing broodstock from local populations is an effective practice to reduce losses of genetic diversity due to hatchery releases, thorough understanding of the underlying genetics of the local wild populations is crucial. Gharrett and Smoker (1993) found that local adaptations and genetic subpopulations existed on small scales within a larger wild pink salmon population. Consideration of the larger wild stock as a single genetic unit had led to reductions in wild genetic diversity.

The remaining seven studies found that hatchery-origin fish had no effect on the genetic diversity of wild salmon populations. A study of long-term effects of a hatchery-origin population of chum salmon in Puget Sound on several nearby wild populations found no decreases in genetic distance between the hatchery stock and the wild stock over time (LeClair et al. 1999). Studies of steelhead supplementation in both Washington and British Columbia similarly found that over time, despite large hatchery releases, conspecific wild populations showed no decrease in genetic diversity (Van Doornik et al. 2010, Gow et al. 2011). In both cases, this was attributed to deliberate broodstock selection with the aim of reducing genetic interactions. A series of studies in Oregon and Idaho found similar results in Chinook salmon, with minimal or no losses in genetic diversity within wild populations in the presence of hatchery-origin Chinook salmon (Matala et al. 2012, Van Doornik et al. 2013, Smith et al. 2014).

A threatened population of steelhead was successfully recovered using hatchery supplementation in Washington (Berejikian & Van Doornik 2018). Genetic diversity increased as a result of the introduction of hatchery fish. The authors attributed this success to the specific methods used in broodstock collection and captive rearing. Embryos, rather than adults, were collected, to pre-empt biases in selection and to capture a wider array of the diversity of the population, while rearing occurred on restricted rations, and at low densities.

Reduction of effective population size

Out of the four studies of effective population size, the effect direction of two were negative for wild fish. A simulation of the effects of hatchery releases on wild populations found that inbreeding was a particular concern (Waples & Do 1994). Without comprehensive marking of hatchery-origin fish or careful broodstock collection, supplementation could do more harm than good. This was mainly as a result of reducing overall effective population size. Indeed, a real-world example was found in a wild population of steelhead in Oregon, where hatchery releases caused a Ryman-Laikre effect that reduced the effective population size by two-thirds, despite doubling the absolute number of fish (Christie et al. 2012).

Two studies found no effect on wild fish. A study seeking a potential reduction in effective population size in wild British Columbia steelhead populations due to hatchery-origin fish found no such reduction (Gow et al. 2011). Endangered wild Chinook runs in California undergoing hatchery supplementation were also found to suffer no reduction in effective population size as a result of hatchery releases, perhaps because the population was already so dangerously close to extinction (Hedrick et al. 1995).

Reduction of fitness

All but one of the six studies of the impacts of hatchery fish on wild fitness found a negative effect. The mechanisms involved in reducing wild fish fitness are diverse. A study of wild Atlantic salmon populations in France found that introgressive hybridization from hatchery-origin fish resulted in changes in life history traits such as fish size and age at return (Le Cam et al. 2015). In a steelhead population undergoing maladaptive shifts in run timing, introgression of hatchery strays was identified as a significant factor among other environmental effects (Robards & Quinn 2002). Similarly, run timing changes in a wild sockeye population in Washington were found to be changing in the direction opposite from expected (Tillotson et al. 2019). Rather than adapting to changes in climate and natural conditions, run timing was changing as a result of hatchery fish influence. A significant portion of a Columbia River Chinook population was found to be hybridized with a hatchery-origin population (Hess et al. 2011). While corresponding fitness consequences were not established for this specific population, the authors noted that similar populations have suffered reduction in fitness as a result of lesser hybridization. This makes it likely that negative results have occurred in the studied population as well. A simulation of negative fitness effects on wild populations from hatchery-origin fish found that integrated production was very likely to lead to reduced fitness of wild fish (Goodman 2005). Integrated production encourages straying of hatchery fish into the wild and incorporates wild fish into the hatchery population. Another simulation study found that there is the possibility to reduce or negate fitness consequences, with the methods depending on the goal of enhancement (Baskett & Waples 2013).

Photo by: Ben Fortini

COMPETITION

Direct competition

Half of the studies of direct competition between hatchery and wild salmon found a negative effect on the wild fish. In controlled treatment enclosures, hatchery-origin Chinook salmon had a negative effect on the growth of wild Chinook salmon (Weber & Fausch 2005). This was found even when density-dependent effects were controlled for by comparing to an equal density enclosure populated solely with wild fish. Hatchery-origin steelhead were found to suppress the growth of resident rainbow trout, a salmonid with a different life history (McMichael et al. 2000). This demonstrates that negative competitive effects are not limited to conspecific interactions. In Japan, a series of studies found negative effects of hatchery stocking on wild salmon. Hatchery-origin masu salmon were found to be superior competitors to wild masu salmon, in controlled enclosures and in the presence or absence of a predator (Reinhardt et al. 2001). Hatchery chum released in Japan were found to reduce growth rates and feeding of wild masu salmon, although the effect was even greater on wild chum salmon (Hasegawa et al. 2014, Hasegawa et al. 2018, Hasegawa & Nakashima 2018). This shows that while interspecies competition can have negative consequences due to behavioural and life history similarities, negative effects on conspecifics are likely to be even greater.

The other half of studies concerning direct competition found no negative effect on the wild salmon. A common theme among these studies was the ability for hatchery releases to fill an existing gap in carrying capacity. No evidence was found for competitive harm to wild Chinook salmon by hatchery-origin Chinook in the Campbell River estuary, British Columbia (Levings et al. 1986). This was attributed to abundant natural resources being capable of supporting the hatchery fish without reducing food availability for the wild fish within this specific habitat. A modelling and simulation approach for chum salmon in Alaska predicted that the wild population was not at carrying capacity based on the resources of the system (Orsi et al. 2004). Therefore, hatchery releases would not result in negative competitive effects. Indeed, owing to release strategies aiming to partition resources and habitat between wild and hatchery chum salmon in Alaska, no negative consequences of competition were found (Sturdevant et al. 2012). A controlled experiment in a laboratory stream channel found that the superior competitive ability of hatchery Chinook salmon was due to larger size and numbers (Peery & Bjornn 2004). This suggests that reducing size at release and quantity of releases would be effective at limiting competition. In two Washington streams, hatchery releases of Chinook and coho salmon were found to have no effect on wild salmon sharing the freshwater environment (Riley et al. 2004). This resulted from already low numbers of wild fish and limited density of hatchery releases. Similar results were found for steelhead in an experimental stream channel (Tatara et al. 2011). The presence of hatchery fish was even found to slightly reduce predation on wild fish, due to predator swamping effects as a result of increased fish density in the environment.

Displacement

Five studies of wild fish displacement by hatchery fish found no effect whereas two studies reported a negative effect. Those two studies found that hatchery-origin steelhead, which had an average body size larger than wild steelhead and resident rainbow trout, displaced those wild fish from the habitat upon being released (McMichael et al. 1999, McMichael et al. 2000). In both of these studies the hatchery fish were able to displace the wild fish even though the wild fish had already established residence. The competitive superiority of the hatchery-origin steelhead was a stronger factor than the wild fish advantage of arriving first.

A study of Atlantic salmon in controlled enclosures found that the ability to occupy prime shelters in the habitat by wild fish before the arrival of hatchery fish was enough to prevent displacement (Orpwood et al. 2004). This remained true even when hatchery-origin fish were introduced in much greater numbers. Four studies that were previously discussed in the direct competition section also investigated displacement. In all cases displacement was not observed to occur (Levings et al. 1986, Peery & Bjornn 2004, Riley et al. 2004, Weber & Fausch 2005), even if other negative effects from direct competition were reported (Weber & Fausch 2005).

Predation

In a review of predation on subyearling wild salmonids by yearling hatchery salmon, it was found that some level of predation is likely to occur in all systems where this coexistence of wild subyearlings and hatchery yearlings is found (Naman & Sharpe 2012). This predation was predictably found to increase in correlation with the percentage of wild fish that had migrated out of the environment prior to hatchery releases, resulting in a suggestion that these releases should be timed accordingly.

POPULATION MIXING

Replacement

The eight studies concerning the replacement of wild fish by hatchery fish universally found negative effects. In the Strait of Georgia, the mixed population of coho salmon was found to be dominated by hatchery-origin fish (Sweeting et al. 2003[2]). After three decades of hatchery releases, the hatchery salmon made up an estimated 70% of the coho mixed in the Strait of Georgia. In the Salmon River of Oregon, cessation of hatchery releases into a mixed coho population resulted in a rapid increase in the wild population (Jones et al. 2018). This population was previously dominated by hatchery-origin fish, showing that they had indeed been limited and replaced by the hatchery fish. A study of Chinook salmon, coho salmon, and steelhead trout in the Klamath River Basin, California, found that increased hatchery releases were maintaining the current numbers as wild salmon abundance continued to decline (Quinones et al. 2014b). This showed a gradual replacement effect, where the mixed population was not increasing in abundance as expected. A study of the mixed pink salmon population in Prince William Sound, Alaska, calculated that the replacement effects were acceptable because the overall number of fish was much greater than prior to enhancement (Wertheimer et al. 1998). However, a later study of the same population found that these risks might have been underestimated (Amoroso et al. 2017). This was because wild fish were unable to increase in numbers when environmental conditions improved, as hatchery-origin fish were already so numerous. Studies of Atlantic salmon in the Baltic Sea, chum salmon in Russia's Kurlisky Bay, and masu salmon in Japan's Shari River all found a similar effect, where wild fish were replaced in the mixed population by hatchery fish, rather than supplemented (Eriksson & Eriksson 1993, Zhitovsky et al. 2012, Sahashi et al. 2015).

Straying

All four studies of straying found a negative effect on wild salmon. In Iceland, the influence of hatchery-origin Atlantic salmon strays was found across several distinct subpopulations in a single river system (Gudmundsson et al. 2013). Future eradication of this local diversity was predicted due to the hatchery releases. Large-scale hatchery releases of coho salmon along the coast of Oregon resulted in straying of hatchery-origin fish into every single basin examined, regardless of whether releases occurred in each basin (Weitkamp 1997). A study of hatchery-origin Chinook salmon in the Elk River, Oregon, found that the siting of a hatchery required returning fish to pass through high-quality spawning grounds, which led to an increase in straying (Pollock et al. 2020). Efforts to reduce straying by separating the run time of a hatchery steelhead population in Eagle Creek, Oregon, from the conspecific wild population, were unsuccessful, as straying was still observed to occur (Brignon 2017).

FISH HEALTH

Disease spread

Three out of four of disease spread studies found no effect on wild fish from hatchery conspecifics. In British Columbia's Cowichan River, hatchery-origin Chinook salmon were not found to have a higher load or diversity of parasites than did their wild conspecifics (Thakur et al. 2018). It is therefore unlikely that hatcheries were a source of pathogen spread. Across several British Columbia water bodies, a similar effect was found for coho salmon, with no significant difference in parasite load or diversity between hatchery-origin and local wild fish (Nekouei et al. 2019). Hatchery practices in the Keogh River, British Columbia successfully limited disease in hatchery steelhead but these fish were subsequently infected by wild fish post-release, a rare example of a negative impact of wild fish on hatchery fish (Halpenny & Gross 2008).

In the Klamath River of Oregon and Northern California, hatchery Chinook releases were found to be correlated with levels of a myxozoan parasite, *Ceratonova shasta* (Robinson et al. 2020). Wild abundance was uncorrelated, drawing a convincing link between the hatchery fish and the abundance of this parasite in the wild. This was the only study of the four to find a negative effect.

Vaccination

An individual-based modelling simulation found that there could be potential benefits to wild salmonid populations if hatchery-origin fish were provided with immunity to common diseases in the wild (Ivan et al. 2018). The benefits would be greatest in systems where fish density as well as mortality due to disease are high, because these populations are likely well below natural carrying capacity due to disease. It should be noted, however, that this is one simulation model and that this idea has never been tested in the natural environment.

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[2] More recently see Beamish and Neville. 2021. Fisheries, 46(11): 539-551. The proportion of hatchery fish in the Strait of Georgia has decreased as the numbers of coho salmon released from hatcheries decreased.

OUTCOMES-BASED STUDIES

Productivity

Of the 14 studies that examined outcomes of wild fish productivity as a result of interactions with hatchery-origin fish, half of these studies (seven) found a negative outcome. Reductions in productivity were observed for: Oregon coho (Nickelson 2003, Buhle et al. 2009); Oregon steelhead (Chilcote 2003, Kostow & Zhou 2006); Alaska chum (Ruggerone et al. 2012); Idaho Chinook (Venditti et al. 2018); and for coho, steelhead and Chinook across Idaho, Oregon, and Washington (Chilcote et al. 2011).

Seven studies found no reduction of productivity attributed to hatchery-wild interactions, in the following taxa and regions: British Columbia sockeye (Price & Connors 2014); Oregon and Washington steelhead (Lister 2014, Courter et al. 2019); Washington coho (Sharma et al. 2006); Washington Chinook (Fast et al. 2015); Chinook across the entire Pacific Northwest (Nelson et al. 2019); and Atlantic salmon in Scotland (Glover et al. 2018).

Size at return

The single size at return study found a negative outcome. Increases in overall abundance of pink salmon in Prince William Sound, Alaska, have occurred as a result of hatchery releases (Wertheimer et al. 2004). However, wild pink salmon in this system have shown a decrease in size at return over time, attributed to density-dependent effects of competition due to sharing the environment with large numbers of hatchery-origin fish.

Survival

Half of the six survival studies found a negative outcome. Two runs of Klamath River Chinook in California showed a negative correlation between abundance of hatchery returns and wild fish survival, among other contributing effects (Quinones et al. 2014a). It is possible for negative outcomes may also result from environmental conditions; wild Snake River Chinook salmon in the American Pacific Northwest were shown to have reduced survival as a result of hatchery Chinook releases only in years where ocean conditions were unfavorable, suggesting that the reduction of carrying capacity leaves the wild fish at a competitive disadvantage to the hatchery-origin fish (Levin et al. 2001). Snake River Chinook were also found to show reduced survival as a result of the presence of hatchery-origin steelhead, though this relationship was not apparent with wild steelhead, highlighting the complicated and sometimes counter-intuitive nature of hatchery-wild interactions (Levin & Williams 2002).

Three studies found no effect on wild survival as a result of hatchery releases: Puget Sound steelhead (Sobocinski et al. 2020); coho and Chinook salmon in Scott Creek, California (Hayes et al. 2004); and in a review of Oregon coho salmon, Japanese chum salmon, and Alaska pink salmon (McNeil 1991).

Photo by: Collin Middleton

SUMMARY OF RECOMMENDATIONS

This section compiles the recommendations made by the authors of the studies included in this review. Because of the broad scope of the review, these recommendations are sourced from authors representing different countries and research focus. Additionally, the applicability of any individual recommendation will depend on the goals and procedures of a hatchery program. The main categories of recommendations include limiting the interactions from occurring to reduce negative effects; implementing best practices in hatcheries; refocusing the priorities and approach of hatcheries; using adaptive management practices; and weighing external factors such as environmental degradation, climate change, and social and cultural concerns. Each of these categories of recommendations are summarized in detail below.

LIMITING INTERACTIONS

The most common recommendations made in the literature included in this review center around limiting the possibility for hatchery-wild interactions to occur in the first place. Some authors recommended cessation of hatchery releases wherever wild fish are present, noting that while short-term catch may suffer, the risks of long-term harm to wild salmon from hatcheries are too great (Hilborn 1992, Sahashi et al. 2015). Moreover, because the effects on wild salmon could be long-lasting, especially in the case of genetic effects, preventing interactions should be part of production planning (Levings et al. 1986, Waples 1991).

One option for preventing interactions rather than attempting to mitigate their consequences afterwards would be the creation of protected areas containing wild salmon runs where enhancement is prohibited (Heggberget et al. 1993). This approach would only address freshwater competition however, leaving open the possibility for high seas competition. Another possibility is the exclusion or reduction of hatchery releases in the presence of stocks at risk (McMichael et al. 1999, Reisenbichler & Rubin 1999). Systems with large, stable wild populations could be more resilient to interactions with hatchery fish, making them good candidates for enhancement (McMichael 2000). On the other hand, a healthy wild system has little to benefit from enhancement (Nickelson 2003). The siting of hatcheries in systems with no wild population may have been successfully implemented with pink and chum salmon in Alaska (Smoker et al. 2000). However, these hatchery-origin fish do interact with wild salmon in the marine environment. Several examples exist of wild populations recovering following the cessation of hatchery releases, lending credence to the approach of limiting interaction in the first place (Chilcote 2003, Kostow & Zhou 2006, Jones et al. 2018).

A related series of recommendations concerns the use of hatcheries where the natural carrying capacity of the system is not being met. If a wild population is accurately determined to be below the natural carrying capacity, enhancement can increase abundance and overall productivity without limiting the wild population (Orsi et al. 2004, Sharma et al. 2006). It has been noted that estimates of natural carrying capacity are a capable predictor of the efficacy of hatcheries (Lister 2014, Zhivotovsky et al. 2012).

HATCHERY PRACTICES

A frequently occurring recommendation is that broodstock should be sourced from local wild populations (Egidius et al. 1991, Reisenbichler & Rubin 1999, Hayes et al. 2004, Zaporozhets & Zaporozhets 2004, Van Doornik et al. 2010, Gow et al. 2011, Hess et al. 2011, Fast et al. 2015, Le Cam et al. 2015, Brignon 2017). This serves to preserve as much of the genetic integrity of the system as possible, and to mitigate genetic risks from introgression of hatchery-origin fish into the wild population. A comprehensive understanding of the genetic structure of the local wild population is essential (Cross et al. 1991, Gharrett & Smoker 1993, Thomas & Mathisen 1993, Gudmundsson et al. 2013). This entails a refinement of the concept of local broodstock, because even a single river system can hold genetically distinct subpopulations with valuable local adaptations that should be maintained.

Another frequent recommendation is to reduce domestication of hatchery-origin fish (Maitland 1986, Thorpe 1991, Cross et al. 1991, Reisenbichler & Rubin 1999, Flagg et al. 2000, Zaporozhets & Zaporozhets 2004, Austin et al. 2021). This includes any genetic, physical, or behavioural deviations from the wild population, whether intentionally to produce more desirable fish for harvest, or unintentionally as a result of rearing conditions. Hatchery-origin fish released at sizes or life stages that will make them larger than wild conspecifics was also noted as a factor to be considered (McMichael et al. 1999, McMichael et al. 2000, Reinhardt et al. 2001, Peery & Bjorn 2004, Hayes et al. 2004, Tatara et al. 2011, Naman & Sharpe 2012, Hasegawa & Nakashima 2018). These larger fish can be more effective competitors or even predators of wild salmon.

Large hatchery releases can also cause competition with comigrating wild salmon and some authors have suggested that release size be moderated to reduce negative density-dependent effects (Nickelson 2003, Peery & Bjorn 2004, Tatara et al. 2011, Hasegawa et al. 2014). However, hatchery releases may also be beneficial to wild salmonids if they result in predator swamping (Tatara et al. 2011). Prudent hatchery practice should therefore focus on quantity of release, as well as the nature of the fish being released.

Several recent studies recommend a series of 'best practices' for hatchery operations along with novel techniques to limit negative hatchery-wild interactions (Fast et al. 2015, Berejikian & Van Doornik 2018, Hagen et al. 2019, Tillotson et al. 2019, Pollock et al. 2020, Johnson et al. 2021). Reduced rearing densities allow for a more natural rearing environment, reducing domestication selection and competition in the wild. Strict disease management will ensure that most fish in the hatchery remain healthy, while those that are not must not be released. Random broodstock collection and factorial mating serve to increase effective population size. Hydraulic embryo collection has been shown to avoid selection pressures by raising broodstock from an earlier life stage, although many other existing best practices also serve to minimize unwanted selection pressures. Widespread genetic testing and screening of broodstock can also serve as a powerful diagnostic tool for genetic conditions in the hatchery population. Also important are considerations of phenological adaptations such as run timing, especially in the context of climate change. Adding a distinct odor to hatchery water as an olfactory clue for returning fish could be used to reduce straying. Finally, pressure-induced triploidy can be used to release sterile hatchery-origin fish that cannot pass genes into wild populations.

PRIORITIES AND APPROACH FOR HATCHERY OPERATIONS

Another recurring theme in the literature examined in this study centers on the ideological basis of hatcheries. Many authors advocate for a cautious approach to enhancement (Waples 1991, Washington & Koziol 1993, Waples & Drake 1998, Lichatowich et al. 1999, Pearsons 2008, Buhle et al. 2009, Chilcote et al. 2011, Kostow 2012, SEP 2013, Berejikian & Van Doornik 2018). They cite the overall lack of research into many types of interactions as a cause for careful consideration of potential risks of hatchery releases, to be balanced against expected benefits to rebuilding, recovery, or harvest. This balancing of risk and benefit should incorporate the 'depressing' effect that hatchery-origin fish can have on wild populations (Chilcote 2003, Sweeting et al. 2003). This effect consists primarily of replacement of wild fish by hatchery fish, but also of other negative consequences to the wild population resulting from the new presence of hatchery fish. An important example of these other consequences is genetic effects (Reisenbichler & Rubin 1999). Another concerns the ecological costs of losses to adaptation and fitness (Grant 2012). For mixed populations exceeding the carrying capacity of the environment, an improvement of environmental conditions that would otherwise lead to increases in wild population growth, can instead have that increase suppressed by the existing hatchery fish (Amoroso et al. 2017).

While this analysis of risks and benefits should take place concerning existing hatcheries, it should also be implemented before commencing any new enhancement programs, as well as continue on an ongoing basis as conditions, knowledge, and technology improves. These recommendations are similar to the established risk framework already in place as an official policy of SEP (SEP 2013).

ADAPTIVE MANAGEMENT

The implementation of adaptive management practices has been commonly recommended throughout the literature, wherein policies and practices are adapted in response to new information and a changing environment (Thomas & Mathisen 1993, Gardner et al. 2004, Matala et al. 2012, Venditti et al. 2018). The goals for each specific hatchery facility must be clearly stated ahead of time and should not change based on failures in a 'moving the goalposts' fashion (Waples & Drake 1998, Gardner et al. 2004, Christie et al. 2012, Baskett & Waples 2013). It has also been suggested that managers take a more comprehensive, ecological, and interspecific approach to the effects of hatchery-wild interactions (Noakes et al. 2000, Levin & Williams 2002, Beamish et al. 2004, Kostow 2012). They must evaluate not only effects on wild conspecifics but also other species that share the environment. This includes management across the entire life cycle, which may span international borders (Cross et al. 1991, Kostow 2012, Ruggerone et al. 2012).

The successful implementation of adaptive management will require a significant increase in wild population monitoring and ongoing analysis of their response to enhancement (Egidius et al. 1991, Hilborn & Winton 1993, Naish et al. 2008, Hess et al. 2011, Matala et al. 2012, Kostow 2012, Van Doornik et al. 2013, Glover et al. 2018). Finally, any comprehensive analyses of the state of hatchery-wild interactions will rely on increased study, as more data are needed to establish long-term effects, strengthen our knowledge of currently studied interactions, and discover potentially unknown effects (Hilborn & Winton 1993, Naish et al. 2008, Kostow 2012, Price & Connors 2014).

EXTERNAL FACTORS

Recommendations from the literature also highlight the importance of external factors, such as environmental degradation, climate change, and social and cultural needs. In many cases addressing initial causes of decline, such as environmental degradation, through habitat restoration can serve the wild population along with or instead of using enhancement (Waples 1991, Waples & Do 1994, Buhle et al. 2009, Kostow 2012). It is also important to consider factors such as climate change (Wertheimer et al. 1998) and social and cultural benefits (Harrison et al. 2018) when performing evaluations of wild salmon and the potential harmful interactive effects of hatchery-origin fish.

CONCLUSIONS

Across the wide body of literature surveyed for this review, the clear message is that interactions between wild and hatchery-origin salmon should be recognized as an important factor and managed appropriately. The majority (50 out of 85) of studies found a negative effect, and this serves as a warning that interactions between wild and hatchery-origin salmon should be a major area of concern for the future.

Due to the format of the review, there are certain limitations to be noted. First, because we are looking for interactions occurring between wild and hatchery fish, there is an expectation that many of the published studies will show a negative effect, since concern regarding these effects is often the driving force behind the research in the first place. Additionally, as with all literature reviews, publication bias threatens to conceal findings that were inconclusive or showed no effect, since they may not have reached publication at all. However, findings of little or no negative effects of interaction would likely be worthy of publication as they still meaningfully contribute to the hatchery effectiveness discussion.

While the overall body of literature is substantial, large gaps still exist due to most studies focusing on a few species, and on a few geographical areas. Considering the immense social, economic, and ecological value of salmon, and the scope of interactions between hatchery salmon and wild salmon, an important message of this review is the relative scarcity of research in Canada. The findings reported in this review are based on a relatively small number of studies, especially in categories such as fish health, and several sub-categories that were represented by single studies.

It is also important to highlight the progress in mitigating hatchery-wild interactions. While early enhancement was carried out using stocks that were domesticated or non-native, British Columbia's SEP was designed to use wild-origin, locally adapted salmon (MacKinley 2004). Later, the development of the SEP Biological Risk Management Framework identified known genetic and ecological risks and mitigation measures (SEP 2013). It is unclear the degree to which these enhancement shifts have led to decreased negative impacts. However, with proper design, monitoring, and learning from successes and failures, improvements in hatchery practices are achievable, resulting in sustained production concomitant with minimizing or eliminating negative interactions with wild conspecifics (Fast et al. 2015).

Significant concerns remain, especially as Pacific salmon continue to face intensifying pressures from climate change, environmental degradation, and overfishing. Implementation of current best practices, and a focus on ecological rather than economic goals, are a solid starting point for adaptive hatchery management. From there, questioning the fundamental assumptions of enhancement, and funneling significantly more resources towards research, development, and monitoring and continuous evaluation, are important steps to take.

The only way to properly evaluate the effects of hatchery-wild interactions, and thus to make informed decisions about where and how to operate salmon hatcheries, is to improve our knowledge through monitoring and research. Critical to this would be quantitative monitoring of natural populations in proximity to hatchery programs. This must be included as a responsibility of the enhancement program to ensure that interactions are assessed broadly and routinely. If, as Pearsons (2008) stated, many of the 'knowns' of these interactions are wrong, and many of the 'unknowns' are not recognized, it is difficult to ask the right questions — let alone find the right answers. Fortunately, all involved share common goals, and continuing to identify, study, and mitigate hatchery-wild interactions will help to secure the continued survival of Pacific salmon for future generations.

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Photo by: Nicole Christiansen

APPENDIX 1 – SEARCH TERMS AND KEY REFERENCES

SEARCH TERMS

Web of Science and Aquatic Sciences and Fisheries Abstracts (ASFA)

[AB=(*Oncorhynchus* OR "*Salmo salar*" OR "Steelhead trout" OR salmon OR salmonid*) OR TI=(*Oncorhynchus* OR "*Salmo salar*" OR "Steelhead trout" OR salmon OR salmonid*)]

AND

[AB=(hatcher* OR enhance* OR artificial OR production OR domestication OR broodstock OR mark* OR introduc*) OR TI=(hatcher* OR enhance* OR artificial OR production OR domestication OR broodstock OR mark* OR introduc*)]

AND

[AB=(wild OR natural* OR ecosystem*) OR TI=(wild OR natural* OR ecosystem*)]

AND

[AB=(consequence* OR cause* OR effect* OR benefit* OR cost* OR risk* OR interact* OR relationship* OR influenc* OR implication* OR affect*) OR TI=(consequence* OR cause* OR effect* OR benefit* OR cost* OR risk* OR interact* OR relationship* OR influenc* OR implication* OR affect*)]

DFO Waves Library

abstract=

(*Oncorhynchus* OR "*Salmo salar*" OR "Steelhead trout" OR salmon OR salmonid*)

AND

(hatcher* OR enhance* OR artificial OR production OR domestication OR broodstock OR mark* OR introduc*)

removed last 2 lines because of low results (33→42→125)

Google Scholar

(*Oncorhynchus* OR "*Salmo salar*" OR "Steelhead trout" OR salmon) AND (hatchery OR enhance OR artificial OR production OR domestication OR broodstock OR mark OR introduced) AND (wild OR natural OR ecosystem)

256 character limit, no wildcards

limited to first 200 results

Photo by: Mitch Miller

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APPENDIX 2

Reference	Study Type	Location	Species	Interaction (broad)	Interaction (specific)	Effect Direction	Effect Description	Takeaway
Hasegawa & Nakashima 2018	Direct experiment	n/a	Masu	Competition	Direct competition	Negative	Evidence for out competition for food of wild fish by hatchery fish	Hatchery-origin masu salmon shown to outcompete wild masu salmon for food.
Hasegawa et al. 2014	Direct experiment	Asia	Chum	Competition	Direct competition	Negative	Evidence for reduced food availability for wild fish due to competition from hatchery fish	Hatchery origin fish can compete with wild fish for food and therefore negatively affect wild growth and survival.
Hasegawa et al. 2018	Natural experiment, comparative	Asia	Chum, masu	Competition	Direct competition	Negative	Evidence for reduced food availability for wild masu salmon due to competition from hatchery chum salmon	Large releases of hatchery chum salmon outcompeted wild masu salmon for food.
McMichael et al. 2000	Direct experiment (control-treatment)	United States	Steelhead	Competition	Direct competition	Negative	Evidence for reduced growth of wild fish in the presence of hatchery fish	The presence of hatchery steelhead negatively affected the growth of wild rainbow trout.
Reinhardt et al. 2001	Direct experiment	Asia	Masu	Competition	Direct competition	Negative	Evidence for reduced survival of wild fish	In the presence of a freshwater predator, hatchery salmon fry outcompeted wild fry and showed greater survival.
Weber & Fausch 2005	Direct experiment	United States	Chinook	Competition	Direct competition	Negative	Evidence for reduced growth of wild fish in the presence of hatchery fish	Presence of hatchery origin Chinook salmon has a negative effect on wild salmon growth.
Levings et al. 1986	Natural experiment, comparative	Canada	Chinook	Competition	Direct competition	No effect	No evidence for competition for food	The presence of hatchery Chinook did not affect the growth of wild Chinook. Food sources of the two slightly differed.
Orsi et al. 2004	Simulation	United States	Chum	Competition	Direct competition	No effect	No evidence for out competition for food resources of wild fish by hatchery fish	Food is sufficiently abundant in the study area - the additional consumption by hatchery fish does not take away food from wild fish.
Peery & Bjornn 2004	Direct experiment	n/a	Chinook	Competition	Direct competition	No effect	No evidence for out competition of wild fish by hatchery fish	Hatchery Chinook salmon did not displace or outcompete wild fish, except when introduced at a larger size or as a result of overcrowding.

Reference	Study Type	Location	Species	Interaction (broad)	Interaction (specific)	Effect Direction	Effect Description	Takeaway
Riley et al. 2004	Direct experiment	United States	Chinook, coho, steelhead	Competition	Direct competition	No effect	No evidence for out competition of wild fish by hatchery fish	Small-scale releases of hatchery fish can be conducted without negative competitive effects on wild fish, when wild fish density is low.
Sturdevant et al. 2012	Natural experiment, comparative	United States	Chum	Competition	Direct competition	No effect	No evidence for out competition for food resources of wild fish by hatchery fish	When management practices aimed at limiting interactions are put into place, hatchery releases can occur without causing competition with wild fish.
Tatara et al. 2011	Natural experiment, comparative	United States	Steelhead	Competition	Direct competition	No effect	No evidence for reduced growth or survival of wild fish due to presence of hatchery fish	When volume and fish size are low enough, a hatchery population can be sustained without negative consequences for wild fish.
McMichael et al. 1999	Direct experiment	United States	Steelhead	Competition	Displacement	Negative	Evidence for competitive dominance and displacement of wild fish by hatchery fish	Perhaps because of increased size, hatchery fish behaviourally dominate wild fish and therefore displace them from prime microhabitat.
McMichael et al. 2000	Direct experiment (control-treatment)	United States	Steelhead	Competition	Displacement	Negative	Evidence for displacement of wild fish in the presence of hatchery fish	The presence of hatchery steelhead displaced wild populations of trout.
Levings et al. 1986	Natural experiment, comparative	Canada	Chinook	Competition	Displacement	No effect	No evidence for displacement of wild fish by hatchery fish	The presence of hatchery Chinook did not displace wild Chinook from the environment.
Orpwood et al. 2004	Direct experiment	n/a	Atlantic	Competition	Displacement	No effect	No evidence for displacement of wild fish by hatchery fish	Hatchery fish were not found to drive out wild fish from prime habitat.
Peery & Bjornn 2004	Direct experiment	n/a	Chinook	Competition	Displacement	No effect	No evidence for displacement of wild fish by hatchery fish	Hatchery Chinook salmon did not displace or outcompete wild fish, except when introduced at a larger size or as a result of overcrowding.
Riley et al. 2004	Direct experiment	United States	Chinook, coho, steelhead	Competition	Displacement	No effect	No evidence for displacement of wild fish by hatchery fish	Small-scale releases of hatchery fish can be conducted without negative competitive effects on wild fish, when wild fish density is low.

Reference	Study Type	Location	Species	Interaction (broad)	Interaction (specific)	Effect Direction	Effect Description	Takeaway
Weber & Fausch 2005	Direct experiment	United States	Chinook	Competition	Displacement	No effect	No evidence for displacement of wild fish by hatchery fish	Presence of hatchery origin Chinook salmon does not displace wild counterparts.
Naman & Sharpe 2012	Literature review	United States	Coho, steelhead	Competition	Predation	Negative	Evidence for high levels of predation on subyearling wild fish by yearling hatchery fish	If large hatchery fish are released in the presence of small wild fish, significant predation is expected to occur.
Robinson et al. 2020	Natural experiment, descriptive	United States	Chinook	Fish health	Disease spread	Negative	Evidence for increased abundance of a parasitic pathogen correlated with hatchery releases	Large hatchery releases correlate with a large increase in the levels of a parasite in a system which also supports a wild population, even while wild abundance is uncorrelated.
Halfpenny & Gross 2008	Natural experiment, comparative	Canada	Steelhead	Fish health	Disease spread	No effect	No evidence for introduction and spread of disease from hatchery to wild	Hatchery practices to prevent releasing diseased fish into the wild were successful, although hatchery origin fish that became residents did catch wild diseases and increased the number of infected fish in the wild.
Nekouei et al. 2019	Natural experiment, comparative	Canada	Coho	Fish health	Disease spread	No effect	No evidence for introduction and spread of parasites from hatchery to wild	Hatchery origin coho salmon do not have a higher parasite load or diversity than sympatric wild fish.
Thakur et al. 2018	Natural experiment, comparative	Canada	Chinook	Fish health	Disease spread	No effect	No evidence for introduction and spread of parasites from hatchery to wild	Hatchery origin Chinook salmon do not have a higher parasite load or diversity than sympatric wild fish.
Ivan et al. 2018	Simulation	United States	Chinook	Fish health	Vaccination	Positive	Evidence for reduction of disease in wild populations	Under disease circumstances of high mortality and high clustering, release of vaccinated hatchery fish can promote reduction (but not elimination) of disease in wild populations.
Amoroso et al. 2017	Natural experiment, descriptive	United States	Pink	Fishery mixing	Replacement	Negative	Evidence for suppressed productivity of wild population due to replacement by hatchery fish	In the presence of a large enhancement program, increases in natural carrying capacity will not result in an increase in wild productivity because hatchery fish are already replacing the potential new wild fish.

Reference	Study Type	Location	Species	Interaction (broad)	Interaction (specific)	Effect Direction	Effect Description	Takeaway
Eriksson & Eriksson 1993	Literature review	Europe	Atlantic	Fishery mixing	Replacement	Negative	Evidence for depletion of wild stocks	When hatchery releases dwarf natural production, and hatchery fish have much greater fresh-water survival. The mixed-stock fishery will support high levels of harvest that will disproportionately deplete wild stocks.
Jones et al. 2018	Natural experiment, comparative, BACI	United States	Coho	Fishery mixing	Replacement	Negative	Evidence for increased abundance of wild salmon after cessation of hatchery releases	When wild fish have been replaced by hatchery released fish, closure of the hatchery was rapidly followed by re-establishment of the wild population in similar abundance.
Quinones et al. 2014a	Natural experiment, comparative	United States	Chinook, coho, steelhead	Fishery mixing	Replacement	Negative	Evidence for 'replacement'- decreases in wild fish abundance tied to increases in hatchery-origin fish abundance	Rather than rebuilding or supplementing a wild population, it is very possible for hatchery operations to entirely replace a wild population.
Sahashi et al. 2015	Natural experiment, comparative	Asia	Masu	Fishery mixing	Replacement	Negative	Evidence for suppressed productivity of wild population due to replacement by hatchery fish	When hatchery fish are released into a system with a natural population, the overall effect is replacement of wild fish, rather than enhancement.
Sweeting et al. 2003	Natural experiment, descriptive	Canada	Coho	Fishery mixing	Replacement	Negative	Evidence for replacement of wild fish with hatchery fish	Hatchery-origin coho have largely replaced wild coho in the Strait of Georgia.
Wertheimer et al. 1998	Natural experiment, descriptive	United States	Pink	Fishery mixing	Replacement	Negative	Evidence for replacement of wild fish with hatchery fish, but many times over in abundance	While hatchery origin pink salmon may have replaced wild fish in PWS, the added abundance is many times greater than the loss of wild fish.
Zhivotovsky et al. 2012	Natural experiment, comparative	Asia	Chum	Fishery mixing	Replacement	Negative	Evidence for replacement of a wild chum population with a hatchery population	Large hatchery releases replaced a locally-adapted series of wild chum populations potentially reducing overall carrying capacity of the system.

Reference	Study Type	Location	Species	Interaction (broad)	Interaction (specific)	Effect Direction	Effect Description	Takeaway
Brignon 2017	Natural experiment, descriptive	United States	Steelhead	Fishery mixing	Straying	negative Negative	Evidence for straying of hatchery fish into the wild population	Even when an earlier run time is successfully maintained in a hatchery population, hatchery-origin fish will still stray and introgress into the wild population.
Gudmundsson et al. 2013	Natural experiment, descriptive	Europe	Atlantic	Fishery mixing	Straying	Negative	Evidence for loss of genetic diversity due to hatchery releases	Even a relatively small river system can contain distinct, locally adapted salmon populations, which are rapidly homogenized by hatchery straying.
Pollock et al. 2020	Natural experiment, descriptive	United States	Chinook	Fishery mixing	Straying	Negative	Evidence for straying	When returning hatchery fish pass through high quality spawning grounds, larger fish and females are more likely to stray, especially in the absence of a unique olfactory cue to the hatchery.
Weitkamp 1997	Natural experiment, descriptive	United States	Coho	Fishery mixing	Straying	Negative	Evidence for straying in all basins along the Oregon coast	Large-scale releases of coho salmon from hatcheries in the Pacific Northwest has resulted in natural spawning of hatchery fish in all studied basins along the Oregon coast.
Austin et al. 2021	Natural experiment, descriptive	United States	Chinook	Genetics	Domestication	Negative	Evidence for introduction and spread of maladaptive traits (domestication) from hatchery to wild	Where wild populations have been observed to adapt to climate change by spawning later in the year, hatchery strays introgressing into wild populations are pushing spawning earlier into the year.
Hagen et al. 2019	Natural experiment, comparative	Europe	Atlantic	Genetics	Domestication	Negative	Evidence for promotion of maladaptive traits	Where domesticated traits were already prevalent in a wild population due to aquaculture escapees, hatcheries disproportionately introduced domesticated individuals back into the wild population due to unintentional selection for domesticated traits during rearing.

Reference	Study Type	Location	Species	Interaction (broad)	Interaction (specific)	Effect Direction	Effect Description	Takeaway
Heggberget et al. 1993	Literature review	Europe	Atlantic	Genetics	Domestication	Negative	Evidence for a risk of loss of genetic diversity in wild populations	When hatchery origin fish are released in the presence of wild fish, risks to the genetics of the wild population are present.
Reisenbichler & Rubin 1999	Literature review	Eco system-scale	All Pacific spp.	Genetics	Domestication	Negative	Evidence for promotion of maladaptive traits	Evidence exists in the literature for the introduction and spread of maladaptive domesticated traits into wild populations of Pacific salmon, resulting in reduced fitness of wild populations.
Thorpe 1991	Literature review	Eco-system-scale	All Pacific spp.	Genetics	Domestication	Negative	Evidence for domestication selection occurring in hatcheries	Genetic changes in hatchery populations, intentional or not, that are adaptive to the captive rearing environment, are not adaptive in the wild and the spread of these changes into the wild population is likely to harm growth/ survival.
Barreto et al. 2019	Direct experiment	Europe	Atlantic	Genetics	Epigenetics	Negative	Evidence for epigenetic effects of domestication being passed to offspring	Epigenetic adaptations to domestication could be responsible for the rapid negative effects of interbreeding between hatchery and wild fish.
Altukhov & Salmenkova 1991	Literature review	Eco-system-scale	All salmon spp.	Genetics	Loss of genetic diversity	Negative	Evidence for loss of genetic diversity due to hatchery releases	Genetic effects stand out as a particularly thorny problem, as loss of diversity in the wild population can reduce present fitness but also ability to evolve into the future and maintain fitness.
Gharrett & Smoker 1993	Natural experiment, descriptive	United States	Pink	Genetics	Loss of genetic diversity	Negative	Evidence for the existence of genetic infrastructure (adaptive variation within a population)	Hatchery straying can lead to losses in genetic diversity even if the broodstock is taken from within that population — diversity exists even at smaller scales.
Johnson et al. 2021	Natural experiment descriptive	United States	Steelhead	Genetics	Loss of genetic diversity	Negative	Evidence for significant genetic introgression from hatchery fish to wild fish	Genetic effects from hatchery programs remain long after hatchery operations cease.

Reference	Study Type	Location	Species	Interaction (broad)	Interaction (specific)	Effect Direction	Effect Description	Takeaway
Youngson & Verspoor 1998	Literature review	Eco-system-scale	Atlantic	Genetics	Loss of genetic diversity	Negative	Evidence for loss of genetic diversity due to hatchery releases	Genetic effects stand out as a particularly thorny problem, as loss of diversity in the wild population can reduce present fitness but also ability to evolve into the future and maintain fitness.
Gow et al. 2011	Natural experiment, comparative	Canada	Steelhead	Genetics	Loss of genetic diversity	No effect	No evidence for reduced genetic diversity in wild populations due to hatchery operations	A supplementation program was able to increase production without decreasing genetic diversity of the wild population.
LeClair et al. 1999	Natural experiment, comparative	United States	Chum	Genetics	Loss of genetic diversity	No effect	No evidence for reduced genetic diversity in wild populations	Despite hatchery releases in the system, wild populations did not become genetically more similar over time to the hatchery population.
Matala et al. 2012	Natural experiment, comparative	United States	Chinook	Genetics	Loss of genetic diversity	No effect	No evidence for loss of genetic diversity in wild population due to hatchery releases	Supplementation can occur without a loss of genetic diversity in wild populations due to the introduction of a hatchery population.
Smith et al. 2014	Natural experiment, comparative	United States	Chinook	Genetics	Loss of genetic diversity	No effect	No evidence for loss of genetic diversity in wild population due to hatchery releases	Implementation of effective management practices can prevent straying and introgression of hatchery fish into wild populations.
Van Doornik et al. 2010	Natural experiment, comparative	United States	Steelhead	Genetics	Loss of genetic diversity	No effect	No evidence for reduced genetic diversity in wild populations	A supplementation program was able to increase production without decreasing genetic diversity of the wild population.
Van Doornik et al. 2013	Natural experiment, comparative	United States	Chinook	Genetics	Loss of genetic diversity	No effect	No evidence for loss of genetic diversity in wild population due to hatchery releases	Despite extensive hatchery operations, no loss of genetic diversity in wild Snake River Chinook was found compared to pre-hatchery samples.

Reference	Study Type	Location	Species	Interaction (broad)	Interaction (specific)	Effect Direction	Effect Description	Takeaway
Berejikian & Van Doornik 2018	Natural experiment, comparative, BACI	United States	Steelhead	Genetics	Loss of genetic diversity	Positive	Evidence for increase in genetic diversity (and abundance) of wild fish due to hatchery releases	A very small and at-risk wild steelhead population appears to have been 'rebuilt' with increased abundance and genetic diversity, by a captive propagation program using collected embryos rather than adults to 'bypass' possible alterations to natural and sexual selection in the hatchery.
Christie et al. 2012	Natural experiment, descriptive	United States	Steelhead	Genetics	Reduction of effective population size	Negative	Evidence for Ryman-Laikre effect, reduction of effective population size due to hatchery fish	Whereas a supplementation program was able to increase steelhead abundance, effective population size was greatly reduced compared to the wild population without enhancement.
Waples & Do 1994	Simulation	n/a	All Pacific spp.	Genetics	Reduction of effective population size	Negative	Evidence for increase in inbreeding/ decrease in genetic viability	Using enhancement for recovery of depleted populations only helps if the original cause for the decline (overfishing, habitat loss/degradation, etc.) is fixed as well.
Gow et al. 2011	Natural experiment, comparative	Canada	Steelhead	Genetics	Reduction of effective population size	No effect	No evidence for a reduction of effective population size due to hatchery operations	A supplementation program was able to increase production without decreasing the effective population size of the overall population.
Hedrick et al. 1995	Natural experiment, descriptive	United States	Chinook	Genetics	Reduction of effective population size	No effect	No evidence for reduction of effective population size due to hatchery releases (Ryman-Laikre effect)	When the natural population is low enough, risks of extinction can outweigh risks of inbreeding depression/Ryman-Laikre effects; in this system no evidence of a reduction in effective population size was detected despite hatchery releases.

Reference	Study Type	Location	Species	Interaction (broad)	Interaction (specific)	Effect Direction	Effect Description	Takeaway
Goodman 2005	Simulation	n/a	All salmon spp.	Genetics	Reduction of fitness	Negative	Evidence for reduction of fitness in wild populations	Integrated production, where wild adults are continually integrated into the hatchery broodstock while hatchery adults are allowed to stray into the natural population, should be expected to reduce the fitness of the wild population and even eliminate what is left of these 'wild' fish.
Hess et al. 2011	Natural experiment, comparative	United States	Chinook	Genetics	Reduction of fitness	Negative	Evidence for loss of fitness due to introgressive hybridization between wild and hatchery fish	Introgressive hybridization between wild Chinook populations and a hatchery stock was observed and theorized to be causing fitness declines in hybrids compared to wild sympatric fish.
Le Cam et al. 2015	Natural experiment, descriptive	Europe	Atlantic	Genetics	Reduction of fitness	Negative	Evidence for introduction and spread of maladaptive traits (domestication) from hatchery to wild	When enhancement is performed using spawners from another water system, outbreeding depression can be caused by introduction of maladaptive traits.
Robards & Quinn 2002	Natural experiment, descriptive	United States	Steelhead	Genetics	Reduction of fitness	Negative	Evidence for changes in run timing	Hatchery releases can change the overall timing of steelhead runs.
Tillotson et al. 2019	Natural experiment, descriptive	United States	Sockeye	Genetics	Reduction of fitness	Negative	Evidence for promotion of maladaptive traits	Inadvertent artificial selection can occur in the hatchery, causing phenological changes that are maladaptive for the wild population — in this case earlier run timing.
Baskett & Waples 2013	Simulation	n/a	All salmon spp.	Genetics	Reduction of fitness	No effect	Evidence for situational effectiveness of both hatchery genetic strategies- 'keep them similar' vs. 'make them different'	While there are situations that suit both the 'similar' and 'different' strategies, generally the worst outcome should be expected from doing neither and ending up with an intermediate 'worst of both worlds'.

Reference	Study Type	Location	Species	Interaction (broad)	Interaction (specific)	Effect Direction	Effect Description	Takeaway
Buhle et al. 2009	Natural experiment, descriptive	United States	Coho	Outcomes-based	Productivity	Negative	Evidence for reduced productivity of wild fish in the presence of hatchery fish	Wild coho salmon productivity was negatively correlated with the number of hatchery coho released, and hatchery-origin fish contributed more strongly to negative density-dependent effects than did wild fish.
Chilcote 2003	Natural experiment, descriptive	United States	Steelhead	Outcomes-based	Productivity	Negative	Evidence for reduction in productivity correlated with proportion of hatchery-origin fish	A negative correlation was found between proportion of hatchery-origin fish in the population, and overall productivity.
Chilcote et al. 2011	Natural experiment, descriptive	United States	Steelhead, Chinook, coho	Outcomes-based	Productivity	Negative	Evidence for decreased reproductive performance	The proportion of fish of hatchery origin in a population is negatively correlated with reproductive performance.
Kostow & Zhou 2006	Natural experiment, descriptive	United States	Steelhead	Outcomes-based	Productivity	Negative	Evidence for decreased productivity	The introduction of a summer-run steelhead hatchery stock in a river with a wild winter-run steelhead stock resulted in a decrease in wild productivity due to competition from hatchery fish.
Nickelson 2003	Natural experiment, comparative	United States	Coho	Outcomes-based	Productivity	Negative	Evidence for reduced productivity of wild fish in the presence of hatchery fish	Wild coho salmon productivity was negatively correlated with the number of hatchery coho released.
Ruggerone et al. 2012	Natural experiment, descriptive	United States	Chum	Outcomes-based	Productivity	Negative	Evidence for reduced productivity of wild fish in the presence of hatchery fish	Asian hatchery-origin chum releases were correlated with Alaskan wild chum productivity, showing an effect from very far away.
Venditti et al. 2018	Natural experiment, comparative, BACI	United States	Chinook	Outcomes-based	Productivity	Negative	No evidence for increase in productivity due to supplementation, no evidence for sustained increase in abundance after supplementation ceases	Enhancement can cause increases in abundance, but this does not necessarily lead to increases in productivity, or mean that the wild population will sustain these increases if enhancement is stopped.

Reference	Study Type	Location	Species	Interaction (broad)	Interaction (specific)	Effect Direction	Effect Description	Takeaway
Courter et al. 2019	Natural experiment, descriptive	United States	Steelhead	Outcomes-based	Productivity	No effect	No evidence for decreased productivity	Environmental factors (hydroelectric dam operations, PDO) are responsible for decline in wild steelhead productivity, not the presence/absence of a conspecific hatchery stock.
Fast et al. 2015	Natural experiment, descriptive	United States	Chinook	Outcomes-based	Productivity	No effect	Evidence for maintenance and/or increase of natural productivity due to enhancement program	Enhancement is able to maintain and sometimes increase the productivity of a natural system, when proper practices are put in place.
Glover et al. 2018	Natural experiment, descriptive	Europe	Atlantic	Outcomes-based	Productivity	No effect	No evidence for increase in productivity due to supplementation	Even detailed understanding of an ecosystem cannot necessarily predict whether hatchery releases will be effective — continued monitoring is essential as negative consequences are not worth it if the purpose of the hatchery is not even being fulfilled.
Lister 2014	Natural experiment, comparative	United States	Steelhead	Outcomes-based	Productivity	No effect	No evidence for increase in natural productivity due to supplementation	If a wild population is at its natural carrying capacity, hatchery operations will not be able to increase natural productivity.
Nelson et al. 2019	Natural experiment, descriptive	United States	Chinook	Outcomes-based	Productivity	No effect	No evidence for reduced productivity of wild fish in the presence of hatchery fish	Seal predation, not hatchery releases, were implicated in the reduction of productivity in wild PNW Chinook.
Price & Connors 2014	Natural experiment, descriptive	Canada	Sockeye	Outcomes-based	Productivity	No effect	No evidence for reduced productivity of wild fish in the presence of hatchery fish	Large releases of hatchery sockeye salmon did not result in decreased productivity of the conspecific wild population in the river system.
Sharma et al. 2006	Natural experiment, descriptive	United States	Coho	Outcomes-based	Productivity	No effect	Evidence for increase in overall productivity without decrease in natural productivity or abundance	With state-of-the-art hatchery operational protocols, it is possible to enhance a system and increase productivity without (short-term) losses in natural abundance and productivity.

Reference	Study Type	Location	Species	Interaction (broad)	Interaction (specific)	Effect Direction	Effect Description	Takeaway
Wertheimer et al. 2004	Natural experiment, comparative	United States	Pink	Outcomes-based	Size at return	Negative	Evidence for a decrease in size at return	Large releases of salmon from hatcheries leads to an overall decrease in mean size at return, due to density-dependent growth in the environment.
Levin & Williams 2002	Natural experiment, comparative	United States	Steelhead, chinook	Outcomes-based	Survival	Negative	Evidence for reduced survival of wild chinook due to hatchery steelhead releases	Even when hatchery releases are found to have no effect on survival of wild conspecifics, other wild salmonid populations can have reduced survival.
Levin et al. 2001	Natural experiment, descriptive	United States	Chinook	Outcomes-based	Survival	Negative	Evidence for reduced survival of wild chinook populations correlated with hatchery releases when ocean conditions are poor	When ocean conditions were poor, hatchery releases were negatively correlated with wild Chinook survival. No correlation existed when ocean conditions were optimal.
Quinones et al. 2014b	Natural experiment, descriptive	United States	Chinook	Outcomes-based	Survival	Negative	Evidence for reduced survival of wild chinook populations correlated with hatchery returns	Two runs of Chinook salmon showed a negative correlation between wild survival and hatchery returns.
Hayes et al. 2004	Natural experiment, comparative	United States	Coho, steelhead	Outcomes-based	Survival	No effect	No evidence for negative effect of hatcheries on wild salmon	A small coastal stream was able to support a small hatchery program without apparent negative consequences to wild conspecifics.
McNeil 1991	Natural experiment, descriptive	Ecosystem-scale	All Pacific spp.	Outcomes-based	Survival	No effect	No evidence for increase in marine salmon abundance over natural carrying capacity due to hatchery releases	As of 1991, three major hatchery programs were not found to have decreased wild fish survival due to overpopulation in the marine environment.
Sobocinski et al. 2020	Natural experiment, descriptive	United States	Chinook, steelhead	Outcomes-based	Survival	No effect	No evidence for reduced survival of wild fish in the presence of hatchery fish	Wild steelhead did not show reduced survival correlated with releases of hatchery-origin Chinook.
Beamish et al. 2004	Case study	Canada	All Pacific spp.	Not determined	Not determined	N/A	n/a (broad overview)	If possible negative effects of hatchery releases are only sought in wild conspecifics, negative effects on other salmonid species sharing the same environment and resources could be overlooked.

Reference	Study Type	Location	Species	Interaction (broad)	Interaction (specific)	Effect Direction	Effect Description	Takeaway
Cross et al. 1991	Literature review	Eco-system-scale	All salmon spp.	Not determined	Not determined	N/A	N/A (high-level review)	Genetic effects, direct and indirect, of hatchery releases on wild populations must be carefully studied and considered in an ongoing basis by hatchery management.
Egidius et al. 1991	Literature review	Europe	Atlantic	Not determined	Not determined	N/A	N/A (high-level review)	A wide-ranging evaluation of risk and benefit should be carried out before it is too late, as salmon hatcheries are already in wide operation in Norway.
Flagg et al. 2000	Literature review	United States	All Pacific spp.	Not determined	Not determined	N/A	N/A (high-level review)	Significant negative interactions between hatchery origin fish and wild fish are occurring, and changes must be made to hatchery management practice especially for those hatcheries that have been operating for a long time.
Gardner et al. 2004	Literature review	Canada	All Pacific spp.	Not determined	Not determined	N/A	N/A	While many risks of negative interaction between hatchery and wild fish have been identified, knowledge and research in many areas is lacking or absent, leading to suggestions for an overhaul in hatchery management.
Grant 2012	Literature review	Eco-system-scale	All Pacific spp.	Not determined	Not determined	N/A	N/A	Hatchery-origin fish are more poorly adapted to the environment than are wild fish, which raises questions about analyses of cost/benefit that look at raw numbers of fish with no concern of quality.
Hand et al. 2018	Literature review	United States	All Pacific spp.	Not determined	Not determined	N/A	N/A (high-level review)	Complex social, political, and historical factors must be considered when evaluating hatchery operations.

Reference	Study Type	Location	Species	Interaction (broad)	Interaction (specific)	Effect Direction	Effect Description	Takeaway
Harrison et al. 2018	Interview-based ethnographic piece	Eco-system-scale	Atlantic	Not determined	Not determined	N/A	Evidence for positive social, cultural, and conservation benefits of hatchery operations	There are many benefits to small-scale hatcheries that are not traditionally measured — social, cultural etc. benefits where individuals feel connected to salmon health and survival. "Official" hatcheries should strive to achieve these benefits as well.
Hilborn & Winton 1993	Opinion piece	Canada	All Pacific spp.	Not determined	Not determined	N/A	N/A	BC's Salmonid Enhancement Program circa 1993 required changes to enable proper evaluation of the program.
Hilborn 1992	Opinion piece	Eco-system-scale	All Pacific spp.	Not determined	Not determined	N/A	N/A (high-level review)	Strong argument is presented against hatchery operations.
Kaeriyama et al. 2012	Literature review	Eco-system-scale	All Pacific spp.	Not determined	Not determined	N/A	N/A	A review from Japan echoes many of the same messages as North American reviews have — hatcheries are likely being used too much, without enough oversight or evaluation of efficacy.
Kostow 2012	Case study	United States	Coho, Chinook, chum, steelhead	Not determined	Not determined	N/A	N/A (high-level overview)	Hatchery programs have a role in a larger management scheme to recover and maintain Pacific salmon — needs to be used properly, carefully, and re-evaluated for effectiveness.
Lichatowich et al. 1999	Opinion piece	United States	All Pacific spp.	Not determined	Not determined	N/A	N/A (historical piece)	The entire basis of hatchery operations is founded on historical and ideological grounds, rather than scientific ones; the way we think about fisheries management needs to be re-evaluated from the ground up.
Maitland 1986	Literature review	Europe	Atlantic	Not determined	Not determined	N/A	N/A	Hatcheries are not clearly effective or worth the potential risks to wild populations.
Naish et al. 2008	Literature review	Eco-system-scale	All salmon spp.	Not determined	Not determined	N/A	N/A (high-level review)	As of 2008, the literature is severely lacking in studies required to fully assess effects of hatchery fish on wild populations.

Reference	Study Type	Location	Species	Interaction (broad)	Interaction (specific)	Effect Direction	Effect Description	Takeaway
Noakes et al. 2000	Literature review	Eco-system-scale	All Pacific spp.	Not determined	Not determined	N/A	N/A (high-level review)	Hatchery-origin fish are replacing wild fish in the PNW and overall abundance and productivity are in decline. Hatchery fish also have negative genetic and ecological effects on wild fish.
Pearsons 2002	Literature review	Eco-system-scale	All salmon spp.	Not determined	Not determined	N/A	N/A	Hatchery fish have effects not only on wild conspecifics but also other species sharing the natural environment.
Pearsons et al. 2008	Literature review	Eco-system-scale	All Pacific spp.	Not determined	Not determined	N/A	N/A (high-level review)	Interactions, positive or negative, do occur and should be considered when deciding whether and how to operate a hatchery, in a risk-assessment based way.
SEP 2013	Literature review and policy overview	Canada	All Pacific spp.	Not determined	Not determined	N/A	N/A	Significant risks and benefits exist in hatchery operations — careful consideration is crucial before commencing any new operations, and ongoing monitoring of risks and benefits is a must for all operating hatcheries.
Smoker et al. 2000	Literature review	United States	Pink, chum	Not determined	Not determined	N/A	N/A (high-level review)	A large salmon fishery has been supported in Alaska due to hatchery releases, and innovations in technology of hatchery operations has increasingly reduced negative effects of the hatcheries on wild populations.
Tatara & Berejikian 2012	Literature review	Eco-system-scale	All Pacific spp.	Not determined	Not determined	N/A	N/A (high-level review)	While experimental data is lacking, theoretical arguments can be made for both wild and hatchery fish having a greater competitive advantage over the other.
Thomas & Mathisen 1993	Workshop	United States	All Pacific spp.	Not determined	Not determined	N/A	N/A (high-level overview)	Adaptive management and stock identification are key to protect wild fish.

Reference	Study Type	Location	Species	Interaction (broad)	Interaction (specific)	Effect Direction	Effect Description	Takeaway
Utter 1998	Literature review	Ecosystem-scale	All Pacific spp.	Not determined	Not determined	N/A	N/A (high-level review)	Hatchery operations should be established and maintained only in a systematic and cautious way.
Waples & Drake 1998	Literature review	Ecosystem-scale	All Pacific spp.	Not determined	Not determined	N/A	N/A (high-level review)	A comprehensive risk/benefit analysis framework should be used before commencing any hatchery operations.
Waples 1991	Literature review	Ecosystem-scale	All Pacific spp.	Not determined	Not determined	N/A	N/A (high-level review)	In many situations, the risks outweigh the potential benefits of hatchery operations.
Washington & Koziol 1993	Literature review	Ecosystem-scale	All Pacific spp.	Not determined	Not determined	N/A	N/A (high-level review)	Numerous negative effects occur on wild populations as a result of hatchery operations, and while enhancement and supplementation are powerful tools, when used indiscriminately they can decimate wild stocks.
Zaporozhets and Zaporozhets 2004	Literature review	Asia	All Pacific spp.	Not determined	Not determined	N/A	N/A	Hatchery operations in Russia have been largely carried out with practices that endanger wild fish and without oversight or evaluation of risk vs. benefit.

Photo by: Nicole Christiansen


Photo by: Eiko Jones

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