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Salmon Against Humanity: Are Hatcheries a Part of Salmon Recovery?

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Where do Hatcheries Fit into Salmon Recovery?

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Tribal Lands Statement

I would like to begin by acknowledging that we gather today on the ancestral homelands of the Coast Salish Peoples, who have lived in the Salish Sea basin, throughout the San Juan Islands and the North Cascades watershed, from time immemorial. Please join me in expressing our deepest respect and gratitude for our Indigenous neighbors, the Lummi Nation and Nooksack Tribe, for their enduring care and protection of our shared lands and waterways.

Introduction

For over fifty years, the city of Issaquah, Washington has celebrated the annual return of salmon to Issaquah Creek with a festival. During the first weekend in October, the main street of the town is lined with stalls selling locally made artwork, jewelry, and food products. People fill the streets to watch the parade, local high schools show off their club activities, and at the center of it all is the Issaquah Salmon Hatchery. This hatchery, constructed in 1936, has been a central part of Issaquah's history and has become nearly synonymous with the community (Friends of the Issaquah Salmon Hatchery 2023). In this context, the community perspective of the hatchery is overwhelmingly positive. It is associated with an exciting festival. Visitors can watch returning salmon make their way through the ladder or leap against the weir in an attempt to get upstream. During the rest of the year, salmon fry or rainbow trout are on site in the raceways for people to see.

Issaquah is only one example. Hatcheries have been in place since the first facility was built on the Columbia River in 1877 and have become deeply ingrained in the fabric of salmon management. They were implemented as a technological solution to declining salmon harvests as a means to supplement the naturally-occurring population. This is still their purpose. They are intended to increase the overall numbers of salmon through the implementation of artificial propagation. The hatchery process has raised stocks from seven species from the family Salmonidae: chum, pink, sockeye, coho, and Chinook salmon as well as steelhead and cutthroat trout. However, salmon returns are still, famously, declining. There are dozens of salmon hatcheries in Washington alone. There are even more in Alaska, Oregon, and California. With all of these facilities and numbers still declining, hatcheries have come under plenty of scrutiny for their effectiveness and place in the future. And truthfully, there is plenty of evidence against hatcheries. Even if they successfully release a huge number of salmon, the quality of those fish are in question as survival rates plummet.

In the hatchery, reproductive material is harvested from the returning salmon. Eggs from the females are fertilized with milt (sperm) from the males and left to incubate in the hatchery's designated facilities. From those eggs, tiny fish with leftover yolk sacs attached to their bellies emerge. These creatures, called alevin, absorb their yolk sacs and become fry and, by this point, are moved out of the incubation to larger chambers in order to continue growing. After even more growth, the fry are moved to ponds or raceways on site where they remain until they grow large enough to undergo smoltification, the process by which they mature into smolts and become ready for life in the ocean. Under natural circumstances, smoltification occurs during outmigration which means that the salmon are adapted to the increasingly saline waters. Depending on the species and life-history type, this could take anywhere from a couple weeks to a couple years. Once they are ready, the young salmon will be released into the stream where they begin migrating to the ocean. Some may linger in an estuary or other nearshore environment before proceeding to the ocean. Salmon stay in the sea for two to seven years, depending on the species, maturing in the productive marine environment, before returning to their natal streams to spawn. And from there, the process repeats again. But from the time that they leave the hatchery up until their return, hatchery salmon are exposed to very different circumstances and pose a number of potential problems.

Salmon are fascinating animals with a complex life history that involves miles of migration and complicated physiological changes from freshwater to saltwater life. Salmon are central factors to several Indigenous tribes and are deeply entwined in the hearts and culture of those peoples. They are also an important source of income, both for the tribes and for the United States of America, through commercial and recreational fishing. Lastly, they serve a vital ecological purpose for other animals that depend on their yearly migration and return and for river flora that benefit from the nutrients that they leave behind. All of this is true for hatchery salmon, but domesticated populations are still markedly different from their wild counterparts. Management by humans has artificially selected characteristics from the salmon population that are effective in the hatchery environment, but potentially limiting in the wild. That management results in genetic and behavioral adaptations that can filter into the wild population, eventually affecting survival rates.

With all of this in mind, there are still paths that hatcheries can take to play a beneficial part in salmon recovery. They are tools that must be utilized with precision and best management practices. Also, like any human-environment interface, they are complex institutions and can serve an educational purpose that aids salmon in the long-term by raising awareness. However, happening alongside all of this, is a rapidly changing world. Salmon are facing many more problems that have nothing to do with hatcheries and, in fact, hatcheries may be a necessary refuge to mitigate some of these problems. Climate change and anthropogenic damage are inevitable at this point and must be considered in the overall salmon crisis.

This paper is meant to help clarify the uncertainty surrounding hatcheries as a tool in salmon recovery. It is far from exhaustive. Salmon hatcheries are a complex topic with a long history and a wide reach. The concepts within this paper serve as an overview of some noteworthy issues with hatchery practices and identify where changes may improve results. While historically, hatcheries may have caused harm, that does not mean that they cannot be reformed to be better.

Section 1 – Who Needs Salmon?

Hatcheries are one part of a larger issue. The central purpose is maintaining salmon runs for everyone and everything that relies on them. First and foremost, the salmon are owed to the tribespeople who lived and grew alongside them for centuries before Europeans arrived. These people have a long and complex history with salmon that must be included in any decision surrounding salmon and their recovery. Some of that history, as well as lawful obligations to the tribes, will be discussed. In addition to the tribes, salmon are a huge economic resource for people in general. It is a popular seafood, a coveted recreational prize, and a means of earning income. Last, but certainly not least, salmon are a vital part of their ecosystems and a significant pathway for marine-derived nutrients to travel inland from the ocean. Numerous animals and plants benefit from stable salmon runs and are being harmed by the overall loss of fish.

1.1 Tribal Rights and Hatcheries

There are many different tribes, each with their own unique experiences, so it must be recognized that the histories and situations described in this section will not be applicable to all tribal entities and their relationships to salmon and salmon hatcheries. Secondly, there are a number of other places to learn about Indigenous culture, history, and activism. However, it would be flawed to write about salmon in any capacity without discussing the tribes and their inherent and treaty rights to fish. Here, the focus will be on salmon's presence in tribal life, historical treaties surrounding tribal fishing rights, and how hatchery production helps to maintain those fishing rights.

Indigenous management is guided by multigenerational sustenance and reciprocity (Atlas et al. 2021). There are many narratives that caution against preventing salmon from reaching their spawning grounds or impeding another group's right to fish (Ritchie and Angelbeck 2020). Fisheries management in general is more of a management system for humans than for fish, considering that culture and beliefs restrained the harvest for millennia before legal counts or enforced repercussions enacted by settlers (Campbell and Butler 2010). For tribes that depend on salmon, the fish represents more than food, it is a symbol of renewal as they return every year despite harvest (Taylor 1999). They are part of a deep mythological structure in which the fish sacrifice themselves for the benefit of the human, as long as they are treated well (Lichatowich 1999). Salmon are treated with respect when they are harvested as it is believed that this respect will please the salmon and ensure next year's return (Taylor 1999, Lichatowich 1999). The importance of this respect is exemplified in the First Salmon Ceremony. The first returning salmon of the harvest is captured and treated with the highest gratitude to avoid offending the fish. No part of the fish is wasted except for the bones which are carefully returned to the river in the belief that the fish will regenerate, share stories of its kind treatment by the humans, and return again the next year (Taylor 1999). This deep respect for the salmon ensures its continued survival which, in turn, grants prosperity to the tribes.

Humans' relationship to salmon changed with the arrival of European settlers, capitalism, and industrialization. The intentional disruption of Indigenous salmon management by colonial authority incited a struggle for control that persists to this day (Atlas et al. 2021). In the process of settlement, a number of treaties were signed in which the tribes ceded their land to the United States in return for several rights, such as the exclusive right to fish at their traditional, or "usual and accustomed", fishing grounds off-reservation (Mulier 2006). These eight treaties, the Stevens Treaties collectively, were signed in 1855 with the various tribes in the land that would eventually become Washington state (WDFW 2023). For example, the Treaty of Point Elliot was signed with the Lummi, Nooksack, Stillaguamish, Swinomish, Upper Skagit, Suquamish, Sauk Suiattle, Tulalip, and Muckleshoot (WDFW 2023). Article 5 of this treaty reads as follows:

> "The right of taking fish at usual and accustomed grounds and stations is further secured to said Indians in common with all citizens of the Territory, and of erecting temporary houses for the purpose of curing, together with the privilege of hunting and gathering roots and berries on open and unclaimed lands. Provided, however, that they shall not take shell-fish from any beds staked or cultivated by citizens" (Governor's Office of Indian Affairs 2023).

Despite these specifications being written into law, tensions rose between the tribes and the colonists. The incoming industrial practices, such as logging, mining, and hydropower, created poor habitat for the salmon, which left fishers, tribal and otherwise, scrambling for a finite resource (Taylor 1999, Brown 2005). In an effort to conserve the fish resource, Washington state authorities targeted tribal fishers, confiscating their tools, arresting them, and assaulting them (Brown 1994). Brutality against tribal fishers reached such a degree that the United States took up a court case against the State of Washington. This case resulted in the Boldt Decision which recognized and upheld the specifications of the Stevens Treaties (*United States v. Washington* 1974). In addition to upholding the treaties, the Boldt Decision entitled the tribes to half of harvestable salmon, established the tribes as co-managers, and stated that laws which affect the off-reservation harvest of the treaty tribes were unlawful (*United States v. Washington* 1974). Sadly, this decision was not met well and was largely ignored until it was upheld by the United States Supreme Court (Brown 1994). The conflict continued further over whether the tribes were entitled to the harvest of hatchery salmon and shellfish. However, the Stevens Treaties and the Boldt Decision laid the necessary groundwork that any following arguments ended favorably for the tribes. Today, the tribes in Washington work together with the state authorities to sustainably co-manage the salmon fishery (WDFW 2023). Cooperation between the American government, Washington State, and the tribes will likely be instrumental for the future of wild Pacific salmon. Movements toward management techniques that are grounded in traditional ecological knowledge are often suggested as ways to protect the fishery for the future (Atlas et al. 2021).

A large portion of the salmon to which the tribes are legally entitled are produced by salmon hatcheries (Ebbin 2011). However, the salmon runs have declined over the decades and some have hypothesized that hatcheries represent part of the problem (the negative aspects of hatcheries are explored later in this paper). Not all of the co-managers in Washington have embraced the perspective of hatcheries as problematic (Ebbin 2011). One Native co-manager stated that the tribes are forced to be pro-hatchery in order to maintain the runs of salmon that they have lived with for so long (Ebbin 2011). Another article, written by Billy Frank Jr., the late chairman of the Northwest Indian Fisheries Commission, acknowledged the amount of harvested fish that originated from hatcheries and called the institutions “necessary tools” (2012). He went on to lament that hatcheries are needed at all, stating that they are not long-term solutions, but without them, the salmon may not survive in what is left of their habitat and the livelihoods of fishermen may be at risk (Frank Jr. 2012). It is important to note that hatcheries are not a replacement for habitat and that they never will be. But singling them out as the only problem obscures the myriad other obstacles that salmon confront.

1.2 Economic Value

Salmon, hatchery or not, are an important economic resource. As a popular purchase at grocery stores and restaurants, they make up a significant portion of Washington’s commercial fishing industry. In 2021, thousands of metric tons of salmon were landed commercially (NOAA 2023). They are also a beloved target of recreational fishers, making salmon a driving factor for investments in equipment, boat rentals, permits, and other necessities for a successful fishing trip. Also, salmon support a number of livelihoods in fields outside of the commercial fishing industry, from sport fishing tours to hatchery maintenance.

The commercial fishing industry in Washington state is structured around multiple species, such as groundfish, shellfish, halibut, and salmon. This industry encompasses a wide range of commercial activities beyond the fish harvesters themselves, such as processors and equipment providers. The estimated value per commercially-caught fish has ranged from $5-70 based on estimates from historic salmon runs in the Columbia River (ECONorthwest 1999). In 2006, over 11 million pounds of salmon were landed, resulting in around $9.5 million in ex-vessel value (the price received by fishers for fish landed at the dock) (TCW Economics 2008). The Lower Columbia region’s catch is particularly dominated by salmon species (TCW Economics 2008). Employment generated by the commercial fishing industry totals over 3,000 jobs, most of which are generated by groundfish, shellfish, and salmon (TCW Economics 2008). Specifically, salmon accounted for about 14% of total income and jobs in the commercial fishing sector (TCW Economics 2008). Although 14% may sound like an insubstantial number, that still amounts to hundreds of jobs and thousands of dollars which make salmon a significant part of the Washington commercial sector. A more recent economic report was prepared in 2017 for the Pacific Salmon Commission, a body formed by the governments of the United States and Canada to conserve salmon. From 2012 to 2015, gross domestic product ranged from 1.2 to 1.8 billion dollars and employment ranged from 17,000 to over 24,000 (Gislason and Lam 2017). In Washington state, Seattle stands out as a major distribution center for out-of-state salmon catch, such as those coming from Alaska (Gislason and Lam 2017). These numbers are much higher than the previously mentioned report due to the inclusion of states other than Washington, such as Alaska, California, and Oregon. Regardless, both of these reports make it very apparent that salmon are an important part of the commercial fishing industry.

However, not everyone fishes commercially. The recreational sector also generates cash flow, albeit sometimes indirectly, and salmon are also very involved in this part of the fishing industry. Some estimates from recent years of high fish abundance have valued salmon at $200 per fish, considering such things as angler expenditures (ECONorthwest 1999). Recreational fishing varies, depending on what the angler wants to do. A charter boat can be hired which means that the angler could purchase a fishing experience with the added value of the operator's experience. Otherwise, the angler can prepare a fishing trip for themselves. From 2012 to 2015, the total gross domestic product from recreational salmon fishing amounted to about $1.3-1.4 billion for North America (Gislason and Lam 2017). Employment ranged between 16,000 jobs to over 19,000 during the same time period (Gislason and Lam 2017). It is worth noting that many jobs in the fishing industry are seasonal, which raises the employment number by a substantial amount. The recreational sector of the fishing industry has a lot of added value, considering the extra expenditures that anglers may spend. For example, in 2006, all fishing-related expenditures in Washington state totaled about $905 million (TCW Economics 2008). This includes a large range of purchases, from transportation to lodging. Additionally, anglers may purchase special vehicles (boats, vans, etc.), equipment (rods, reels, lines, etc.), and other items (magazines, permits, licenses, etc.). From these numbers, anglers targeting salmon were estimated to spend about $58 a day (TCW Economics 2008). The impact of salmon on recreational fishing is somewhat indirect, as not all fishing trips are intended for salmon alone. However, since many anglers seek out salmon, the money involved can be partially attributed to salmon, hatchery or wild.

There is an unspoken understanding that the salmon will return, *must* return, every fall. It is a comfort to adults and children alike when salmon are found in abundance. And increasingly, hatcheries provide a significant portion of the salmon that are harvested. Hatchery salmon are differentiated from wild salmon by clipped adipose fins (a small fin on the back of the fish near the tail). An analysis of recreational anglers in Washington and Oregon found that most people would rather release wild salmon than hatchery salmon, even if the wild salmon are legal to keep (Anderson and Lee 2013). This, at least, signifies that there is a tangible perceived difference between these two types of salmon that anglers are responding to. But without these hatchery salmon, there would be far fewer fish to catch. With fewer salmon, the fishing industry would certainly take a hit.

It only takes a quick Google search to find out how much is spent on salmon hatchery facilities each year. One recent article noted that federal agencies have poured $2.2 billion into aging hatcheries over the past 20 years, amounting to several hundred dollars for each fish that returns to the Columbia River system (Schick and Hwang 2022). With all of this effort going into hatcheries, it would be a disservice to taxpayers if that money were not being used effectively.

1.3 Ecosystem Services

Salmon runs support a wide variety of other animals, such as other fishes, mammals, and birds. Many bird species are documented as predators of juvenile salmon. For example, avian consumption of steelhead smolts in Snake River is very high, suggesting that birds are the greatest source of smolt mortality during out-migration (Evans et al. 2022). These effects vary depending on the proximity of bird colonies and salmon density (Evans et al. 2022). For this particular study, Caspian terns were identified as prominent predators of juvenile salmon, but other birds such as double-crested cormorants and California gulls were also noted (Evans et al. 2022). In the Salish Sea, great blue herons are often spotted near streams where they prey on juvenile salmon. An investigation found that most predation occurred during chick-rearing season with salmon making up to 8.4% of the great blue heron chick diet (Sherker et al. 2021). Similar to Snake River, the proximity of heron nesting sites to salmon spawning streams is an important predictor of predation on salmon (Sherker et al. 2021). Lastly, the signature bird of the United States, the bald eagle, is known to rely on salmon and salmon carcasses as a prey source. During the winter, when other prey is scarce, eagles rely on chum salmon runs to survive (Elliott et al. 2011). Historically, eagle numbers have been closely linked to salmon density, but with the decline of many salmon runs, eagles are forced to search for different food such as waterfowl (Elliott et al. 2011, Duvall 2022). Fewer salmon could have a profound effect on predatory birds, causing them to obtain less food or to concentrate foraging on other species with unpredictable results.

In addition to birds, salmon provide sustenance for several species of marine mammals. For example, between 1970 and 2015 the annual biomass of Chinook salmon consumed by pinnipeds was estimated in a modeling simulation to have increased from 68 to 625 metric tons (Chasco et al. 2017). The decline of Chinook salmon has correlated with an increase in the abundance of pinnipeds, suggesting that predation may play a role in salmon conservation (Chasco et al. 2017). However, pinniped predation is more nuanced than this. Harbor seals consume salmon during smolt outmigration as well as during the return of spawners. In the fall, these seals typically target salmon of lower conservation concern, such as chum and pink salmon (Thomas et al. 2016). In the spring, when smolts are migrating to the ocean, evidence suggests that harbor seals target species of higher conservation concern, such as coho and Chinook salmon (Thomas et al. 2016). These preferences, affected by time of year and species distribution, could signify an important relationship between seal predation and variability in smolt survival.

Pinnipeds are not the only marine mammals that feed on salmon. Many people in Puget Sound are familiar with the Southern Resident Killer Whales. These whales are well-known consumers of Pacific salmon, especially the Chinook salmon (Couture et al. 2022, O'Neill et al. 2014, Hanson et al. 2010). Unfortunately, as salmon populations decline, the killer whales have struggled to find food (Couture et al. 2022). Analysis of fish remains left behind after predation events found that the majority of salmon consumed originated from the Fraser River with less than 15% originating from Puget Sound (O'Neill et al. 2014). Salmon runs in the Fraser River are also declining, which is likely to have a major impact on the whales' diet (O'Neill et al. 2014). Scarcity in salmon is a major concern for the future of the killer whales in particular.

Salmon are much more than prey animals for the magnificent bald eagle or the imposing killer whale. Pacific salmon do the majority of their growth in the nutrient-rich ocean and, when they return to the rivers, they bring those marine nutrients back with them (Cederholm et al. 1999, Mathisen et al. 1988, Kline et al. 1993). Comparison of salmonberry shrubs from stream sites with or without salmon found significant differences in nitrogen concentration (an instrumental component for plant growth), indicating contribution from the salmon (Bilby et al. 2003). Partially consumed carcasses on the shore can be distributed further by scavengers or flying aquatic insects (Schindler et al. 2003). For example, 22 species of mammals and birds were observed to consume fish mass from coho carcasses on the streambank (Cederholm et al. 1989). In the fall, terrestrial and aquatic insects take advantage of the carcasses or enhanced plant productivity, resulting in more food for the birds in the spring (Wagner and Reynolds 2019). The presence of hatcheries means that the distribution of carcasses happens with some help from local volunteers, such as in Oregon where hatchery carcasses are intentionally returned to spawning grounds (Emery 2021). The Washington Conservation Corps also practices this distribution of salmon carcasses in the Chiwawa River (Wooldridge 2019). Although it cannot be said for certain that every hatchery practices this, the benefits of salmon carcasses to their ecosystem are well-known.

Section 2 - What's Wrong with Hatchery Salmon?

The bulk of scientific evidence is against the continuation of hatcheries, at least as they currently operate. They have been referred to as "arrogant half-baked technologies" that are doomed to fail or simply as misleading institutions that present a large danger to salmon (Meffe 1992, Hillborn 1992). In order to understand this situation, it is vital to have a general idea of where hatcheries have gone wrong. It all begins with the choices made by a variety of management institutions, from the individual states to the federal level managers to tribal management authorities. Those decisions lead to physical changes in the salmon. Those changed salmon leave the hatchery, entering a number of possible interactions with their wild counterparts.

2.1. Management Decisions

In 1875, with the salmon canning industry feasting on "unlimited" salmon runs, concerns were rising about the genuine stability of their supply. By this time, the world had already seen the collapse of the Atlantic salmon fishery. Failure to protect habitats and regulate harvest would undoubtedly lead to loss of the Pacific salmon species. Spencer Baird, head of the U.S. Commission on Fish and Fisheries at the time, identified three major threats to the salmon industry: excessive harvest, dams, and disruptions in the physical habitat (Lichatowich 1999). Baird did not believe that restricting the fishing industry would be the answer, citing difficulties with enforcing the proposed laws (Baird 1875). Based off of results from a small hatching station on the Sacramento River, Baird concluded that artificial propagation of salmon would be the panacea to a finite supply of fish (1875). Baird's conclusions are still very applicable today. All three of the threats that he identified are still actively affecting salmon populations (Ruckelshaus et al. 2002). In addition, the hatcheries that he suggested are, obviously, still in place. However, those hatcheries are proving to be far from a full solution.

Many of the failures associated with hatchery salmon can be traced back to the decisions surrounding how the fish were managed. In the past, hatchery managers have been more concerned with quantity over quality, introducing fish that were poorly adapted to their receiving environment and ill-suited for sustained natural production (Brannon et al. 2004). Managers have selected for earlier spawners in order to temporally separate hatchery population from the wild population by mainly collecting reproductive material from the earliest-returning fish (Tillotson et al. 2019). This selection was successful in that the hatchery salmon returned to their natal streams earlier than wild salmon (Tillotson et al. 2019). Unfortunately, several studies at varying hatcheries found that earlier spawning has forced the salmon into warmer summer temperatures (Tillotson et.al 2019, Quinn et al. 2002, Brannon et al. 2004). Salmon are finely tuned to their ecosystems, so much so that managers would not expect transplants to survive well at all in comparison to the local ecotype (Brannon et al. 2004). By choosing hatchery salmon that are asynchronous with the environmental template, hatchery management practices are unintentionally putting the run at a disadvantage.

Another major management decision would be the annual release of hatchery salmon. Large-scale releases have been occurring for decades and concern over exceeding the environmental carrying capacity began to grow in the late 1990s (Beamish et al. 1997). An estimated 300-500 metric tons of hatchery salmon are released in Washington to migrate to the Pacific Ocean (Flagg 2015). Approximately 775-1,300 metric tons of hatchery salmon are released in the Salish Sea, entering a large estuary before continuing into the ocean (Flagg 2015). This is an overwhelming amount of salmon to be released into the ecosystem in a relatively short amount of time. Evidence has indicated that such large releases can have detrimental effects on the naturally-occurring wild populations (Bisson et al. 2002, Kostow 2009). Hatchery salmon have been implicated in a number of risks to natural populations, from genetic drawbacks to competition and predation (Flagg 2015). Additionally, the flood of hatchery salmon masks the size of the wild population, allowing for accidental overharvest of wild salmon (Flagg 2015). There are also cases of hatchery salmon returning in such high numbers that hatchery officials struggled to handle the situation. For example, in California's Klamath basin, the 1995 fall run of Chinook was so numerous that the hatchery was unable to hold all of the fish, which allowed hatchery-origin salmon to spawn throughout the basin, derailing restoration projects for wild salmon (Bisson et al. 2002).

A 2019 study on changes in hatchery practices for Chinook salmon examined how protocols have changed over time in the Salish Sea basin. Diversity of release dates has decreased significantly, with the United States pushing the date to later in the year while Canada opts for earlier release (Nelson et al. 2019). In contrast, naturally occurring salmon migrate to the ocean earlier in the year and over a much longer time frame (Nelson et al. 2019). A similar study in Canada has also confirmed the importance of ocean entry timing in smolt survival (Irvine et al. 2013). Diversity in size at release has also decreased significantly, with Puget Sound salmon being much larger than they once were (Nelson et al. 2019). Although some might argue that bigger is better, the larger hatchery salmon have a greater overlap with the preferred prey size of marine mammals, avians, and other natural predators (Nelson et al. 2019). However, it is true that to some extent, larger smolts have a greater chance at survival (Irvine et al. 2013). Between these two studies, and several others, it seems that there is plenty of evidence that management choices surrounding release times and sizes should be re-evaluated.

There are still plenty of salmon that successfully return to spawn, despite the obstacles that stand in their way. Those salmon are the parents of a new generation, passing on their genomes to their young. In this way, the hatchery creates cohorts of salmon which reflect the selections of the institution: bigger, faster-growing, early returning fish. This brings up another concern for hatchery salmon, one that is the driving set of instructions behind all of the aforementioned traits.

2.2. Genetic Risks

Genetic diversity is the foundation of species adaptability. Populations with a high degree of variation will be more capable of surviving through many different sets of circumstances. Considering the endangered status of several Pacific salmon runs, hatchery effects on genetics are a definite concern. Some commonly raised issues are the risks of inbreeding, interbreeding/outbreeding, and perpetuation of characteristics that are unhelpful in the marine environment.

There have been a number of studies attempting to determine the true impact of hatchery practices on the genetic makeup of salmon subpopulations. For example, in Lilliwaup Creek, the 2002 fall-run of chum salmon was analyzed and found to be mostly descendants from 10 hatchery fish spawned in 1999 (Small et al. 2009). A similar situation was found in Jimmycomelately Creek where a significant number of hatchery salmon were descendants of four fish from 1999 or 37 fish from 2000 (Small et al. 2009). These two subpopulations experienced a dangerous decline in genetic diversity. Strong evidence has shown that the fitness for natural rearing and spawning can be substantially reduced by the effects of artificial propagation which has major implications for the future goal of eventually creating populations that have no need of hatcheries (Reisenbichler and Rubin 1999). Substantial change occurs when salmon are held in captivity for a year or longer as fish that are well-suited to the hatchery environment will have an increased chance for survival (Reisenbichler and Rubin 1999). Essentially, the hatchery has a profound effect on the genetic characteristics of the salmon that are produced which, in turn, results in poor survival beyond the strictly controlled hatchery environment.

It is also important to note that hatchery salmon and wild salmon have opportunities to interbreed and produce offspring. The origin of the salmon may seem arbitrary, but as discussed previously, the hatchery setting has selected for specific characteristics, such as larger size or a faster growth rate. Due to that, hatchery salmon and wild salmon are genetically distinguishable. A long-standing concern of interbreeding is the possible loss of the wild lineage (Bisson et al. 2002). This would be most likely to happen if hatchery salmon and wild salmon diverged from each other genetically, either because of the hatchery environment itself or because of differences in stock origin (Bisson et al. 2002). Indeed, significant morphological differences have been found between hatchery salmon and wild salmon, such as a narrower head and a more compressed body (Wessel et al. 2006). Despite this concern, there is evidence that hybrid individuals (hatchery x wild offspring) are not strongly influenced for better or worse survival rates (Chittenden et al. 2010). In fact, the larger impact tended to come from whether or not the smolts had been reared in a traditional hatchery or in a stream (Chittenden et al. 2010). So while interbreeding is a factor to be considered, the selective pressure of the hatchery environment itself may take precedence.

One particular case study, taking place in Minter Creek, Washington, noted that there was a significant decrease in production of young salmon over the history of the hatchery (Ford et al. 2006). Since 1938, when hatchery fish were first released into the creek, there were no sustained attempts to separate the wild population from their hatchery counterparts (Ford et al. 2006). Over the years, the genetic makeup of the Minter Creek population would have changed to reflect characteristics selected by the hatchery rather than those selected by the natural environment. It was concluded that the impacts of the hatchery were a probable contributor to the decrease in smolt outmigration as the years passed (Ford et al. 2006). Since the start of large-scale hatchery releases, the Minter Creek population was most likely comprised of hatchery salmon. Examination of natural and hatchery genotypes found that the two were very similar, implying that the characteristics of the wild salmon were replaced by those of the hatchery (Ford et al. 2006). Considering this example, concerns about the loss of wild salmon are very plausible.

Finally, more recent research has suggested that the reduction in fitness may be caused by epigenetic reprogramming rather than outright differences in genotype. Epigenetic reprogramming is a modification in gene expression that is a result of external stimuli. In this case, the hatchery salmon were found to have a higher proportion of methylated genes than their natural-origin counterparts (Le Luyer et al. 2017). This suggested that something about the hatchery environment made it beneficial to leave those genes unexpressed. However, since those genes were expressed normally in natural-origin fish, this reprogramming is a potential explanation for lower relative survival of hatchery salmon (Le Luyer et al. 2017). It is also important to recognize that these modifications were found independently in two genetically distinct populations (Le Luyer et al. 2017). These results have been replicated in coho salmon from Canada, finding that environmentally-induced changes have persisted in germ cells of adults until their reproduction (Leitwein et al. 2021). The differences in methylation patterns found in other studies are consistently found in the sperm of hatchery fish which is a potential source of multigenerational transmission (Koch et al. 2022). Therefore, the hatchery environment is likely producing salmon that are relatively unsuited for the environment that they will face outside of the raceways.

2.3. Domestication Effects

“Domestication” and “domestication selection” are terms commonly associated with the ways that humans cultivate nature, including salmon in hatcheries. Domestication applies to genetic changes that are direct or indirect results of human efforts to control the relationship between a population and its environment (Waples 1999). Domestication selection refers to the process by which the changes happen (Waples 1999). For example, if hatchery employees choose early-returning spawners to create the next generation of fish, the genetic profile of the population may shift toward those early-returning spawners. The choice of spawners is selection and the long-term change in the population is evidence of domestication.

There are two factors that will inevitably alter the hatchery population. First, the hatchery environment is different from the natural environment in multiple ways. Secondly, the point of a hatchery program is to successfully rear more salmon that would occur in the wild (Waples 1999). The egg-to-fry survival rate in hatcheries is 85-95% in comparison to 1-5% in the wild, meaning that there is less selective pressure (Reisenbichler et al. 2004). In other words, fish may not have survived in the wild can live safely in the hatchery. It is also worth noting that, although the hatchery salmon will be exposed to the process of natural selection after leaving the hatchery, the effects of domestication will still remain. Certainly, for individuals with disadvantageous traits, survivability will be lower and some aspects of domestication will be culled from the population as those fish fail to return. However, the odds of natural mortality cancelling out domesticated fish entirely are very low (Waples 1999). Additionally, if this were to happen, there would be no benefit to the hatchery program in the first place because supplementation would not occur.

The effects of domestication have been documented in a number of cases. A stock of salmon was selected for their size over 18 generations and then compared to their unselected parental stock (Neely et al. 2012). Once the fish had hatched, there was a definite difference between the domesticated stock and the parental stock. The domesticated stock displayed a significantly higher efficiency at utilizing their yolk, 35.1 % better than the parental stock (Neely et al. 2012). An additional effect of domestication is altered predator avoidance behavior in salmon fry. In a laboratory test on Quinalt wild fry and a local hatchery population, the wild fry survived predation significantly better than the hatchery fish (Berejikian 1995). Visual exposure to the predator improved avoidance in both sets of fry, implying that this experience is necessary for better survival rates (Berejikian 1995). The predator-free nature of the hatchery is detrimental to the salmon produced, creating a more naïve behavioral pattern through domestication selection.

It should also be noted that the effects of selection in the hatchery environment can be detected within a single generation. For example, vulnerability to predators has been detected in hatchery salmon on a small scale after only one generation of cultivation (Fritts et al. 2007). This makes sense, considering how predation in hatcheries is practically non-existent, barring the occasional invading bird. The lack of predation may influence young salmon in developing risky behavior (Fritts et al. 2007). First-generation steelhead trout in hatcheries were found to grow at a faster rate but survived at a lower rate when they were placed in a stream environment (Blouin et al. 2021). The contrast was small, but present, which implied the severity of selection pressure in the hatchery if not managed correctly (Blouin et al. 2021). Offspring of first-generation hatchery steelhead demonstrate a clear adaptation to captivity due to higher mortalities once leaving the hatchery (Christie et al. 2004). From these results, it is clear that selection in hatcheries takes place on a very short time scale.

Noticeable differences appear in domesticated salmon over such a short time period which makes hatchery salmon an ideal example to study the early effects of domestication. Within a handful of generations, hatchery salmon can be genetically differentiated from their parental populations (Eun Kim et al. 2004). A potential mechanism for the speed of these adaptations could be differentially expressed genes (DEGs). These genes have different amounts of messenger RNA (mRNA), which are proxies for the amount of proteins produced (Bull et al. 2022). Across the plethora of studies that have been conducted on hatchery salmon, a few broad patterns emerged in the represented fish which included Chinook and coho salmon, and rainbow/steelhead trout. An analysis of the underlying physiological changes has shown that most functional pathways for muscle are upregulated in hatchery fish, relative to wild fish, meaning that the body has been altered specifically to support larger overall growth (Tymchuk et al. 2009). Domesticated salmon also trend toward weaker immune responses which may be due to energy limitations (Bull et al. 2022). Fish that are selected for growth will allocate their energy reserves to growth which might reduce the energy available for other bodily functions, such as the immune system. Domesticated fish also favor size at the expense of burst swimming speed, putting them at higher risk for predation (Bellinger et al. 2014). Another observed result of domestication on salmon is a reduction in phenotypic plasticity (Bull et al. 2022). Other studies have also found evidence of the rearing environment (the hatchery) influencing gene expression through DNA methylation (Venney et al. 2021). Since domesticated salmon are usually released into a very different habitat after reaching a certain size, a lack of plasticity could certainly prove detrimental.

2.4. Survival

Without a doubt, salmon are changed by their time in the hatchery. The next important thing to consider is how these changes affect the salmon once they leave the rearing environment. When young salmon are released into freshwater, they will eventually migrate into the ocean where they will spend most of their life (2-5 years) growing before returning to their natal streams to spawn. However, the released hatchery salmon far outnumber those that return due to natural mortality. They also experience a less successful spawning season in comparison to wild-origin fish (McLean et al. 2003).

Forks Creek Hatchery is located in southwest Washington on a tributary of the Willapa River. Forks Creek supports a population of naturally spawning steelhead trout as well as a non-native population of steelhead that are reared in the hatchery. For a period of two years, the hatchery fish were allowed to spawn with the wild fish, but that practice has been discontinued which means that the area supports two identifiable stocks of steelhead trout. The trout have been sampled since 1996, determining hatchery or wild-origin based on clipped fins and genetic analysis (McLean et al. 2003). In 1997, hatchery females produced an average of 0.16 adults per capita while the wild females produced an average of 6.70 adults per capita. It is possible that this discrepancy in reproductive success is related to early maturation in hatchery salmon which is a byproduct of the rapid growth encouraged by artificial propagation (Ford et al. 2012). In 1997, the hatchery smolts spawned in the wild had a marine survival of 12% in comparison to the wild smolts which survived at a rate of 36% (McLean et al. 2003). Marine survival is not entirely dictated by the hatchery, as productivity in the ocean changes from year to year. However, some dramatic differences have been recorded, such as 1.3% hatchery survival compared with 7.8%-31.5% wild origin survival, which suggests that the hatchery does play a role (Beamish et al. 2012). Overall, several studies in a variety of places have recognized the reduced survival of hatchery salmon.

In an attempt to examine the effect of the rearing environment on survival, one stock of fish was raised at three different facilities (Pelton Ladder, Carson National Fish Hatchery, and Parkdale Hatchery) and released from a common site. The smolts from Pelton Ladder were the largest and most developed in the study and experienced the greatest returns (Beckman et al. 2017). In contrast, smolts from Carson National Fish Hatchery were very small, poorly developed, and showed the poorest survival (Beckman et al. 2017). These results implied environmental influences significantly affected the performance of smolts, depending on their size. Pelton Ladder fish were found to be physiologically similar to the wild fish in the area, undergoing a metabolic change as the seasons transitioned (Beckman et al. 2017). As the temperatures changed, the fish stopped growing and relied on their lipid stores, something that could be replicated with reduced feeding regimes and temperature adjustments (Beckman et al. 2017). Studies have also found that survival of naturally-reared fry (smaller and younger than smolts) is significantly higher than hatchery fry (Harstad et al. 2018, Maynard et al. 2004). In such cases, it may prove helpful to emulate the wild conditions to ensure better survival of hatchery salmon.

Hatchery fish are sometimes transported to different locations, such as moving between facilities or moving to a release point that is nearer to marine waters. Transportation can involve many other stressors that could further impair the abilities of the smolts (Stewart et al. 2017). Stress signals have been found in studies on transportation of young salmon, such as coho yearlings from Fall Creek (Schrek et al. 1989). Recovery of these salmon as adults was reduced when the yearlings were not given enough time to adjust to their migratory stream (Schreck et al. 1989). To further complicate things, there is some evidence that different species of salmon respond differently to transportation (i.e. Chinook being more affected than coho (Congleton et al. 2000)). Thus, it is crucial that the salmon have an acclimatization period before being exposed to saltwater. Juvenile Chinook salmon were moved over a range of times to determine what that time period might be. The results showed that Chinook salmon needed more than three weeks to recover from the stressors of movement before being able to survive in saltwater (Stewart et al. 2017). Experimentation with acclimatization time periods after transportation may be required to find the most favorable periods for survival rates.

An important component of smolt survival is the ecosystem, due to the fact that throughout their lives, salmon migrate through a continuum of habitats (freshwater, estuaries, saltwater), each with their own unique conditions. The survival of coho salmon smolts were examined from 1977-2010 to identify patterns relating to spatial scale (Zimmerman et al. 2015). The primary pattern in the Salish Sea showed that smolt survival declined over the entire study period (Zimmerman et al. 2015). In contrast, the Pacific Coast has showed an increase in smolt survival that now roughly matches the survival rate in the Salish Sea (Zimmerman et al. 2015). The different survival patterns suggest that the early marine environment in the Salish Sea plays a key role in smolt survival. However, the Salish Sea and the Pacific Coast have changed drastically over the decades, even without the presence of hatcheries. In a variable environment, it is even less effective to release salmon with reduced fitness.

2.5. Density-dependent Factors

Hatcheries release massive numbers of salmon annually, usually during a small window of time when naturally-occurring salmon are migrating. The abundance of hatchery salmon has been steadily increasing in recent decades and density-dependent effects are becoming apparent (Ruggerone and Irvine 2018). The increase in releases from salmon hatcheries has a number of implications for interactions between hatchery and wild salmon. Competition intensifies for a limited number of available resources. More salmon may mean easier pickings for predators, or interspecies predation that harms populations of concern (Sobocinski et al. 2021). Hatcheries are also ripe with pathogens that are carried into wild populations with the annual releases. Density-dependent impacts take on many different forms for population control.

In the matter of competition, an important factor to consider would be the species of salmon involved. In cases where hatchery salmon were released to an assemblage of wild species, few distribution changes were observed which implied low potential for interspecific competition (Tatara and Berejikian 2012). However, salmon within the same species will share preferences for similar habitats and food sources, making competition between salmon of the same species much more likely (Tatara and Berejikian 2012). But competition can change with entry into the marine environment. New evidence has suggested that an abundance of pink salmon has a negative impact on chum salmon due to competition in the ocean (Litz et al. 2021). Over the last five decades, chum returns averaged 34% lower during pink salmon years relative to non-pink salmon years (Litz et al. 2021). Similar results have also been found for Chinook salmon where survival decreased with the presence of pink salmon but increased or remained stable without pink salmon (Kendall et al. 2020). Levels of competition can vary depending on freshwater versus saltwater, interspecific vs. intraspecific, and abundance of hatchery and/or wild salmon.

Hatchery salmon can compete with wild salmon without necessarily consuming resources or being aggressive with one another. Instead, wild salmon may be displaced from their territories or from important instream positions by the hatchery salmon (Weber and Fausch 2003). Salmon prefer stream positions that are energetically favorable. For example, they seek out areas where they have refuge from the current but can maintain access to food. When stream positions are limited, it is logical to infer that salmon will be forced into less favorable conditions, consequently suffering from reduced accessibility to food or refugia (Weber and Fausch 2003). Competitive dominance of hatchery coho salmon has also been observed in aquarium settings, despite the prior residence of wild salmon (Rhodes and Quinn 1998). In contrast, during spawning season there is evidence of submissive behavior from hatchery males which prevents successful reproduction (Fleming and Gross 1993). Hatchery females retained larger proportions of eggs and lost more eggs to nest destruction by other females (Fleming and Gross 2003). In this regard, wild salmon are at an advantage, but the failure of the hatchery salmon suggests an incapability to rehabilitate wild populations. It is also another sign of loss of fitness, as discussed in a previous section.

Despite any competitive advantage that hatchery salmon may have in freshwater, they may find themselves at a severe disadvantage in the ocean. As discussed in a previous section, hatchery salmon have displayed relatively poor predator avoidance in freshwater (Berejikian 1995). Wild salmon are able to observe the consequences of naïve behavior (Brown and Laland 2001). Salmon have also been observed to display fright responses to chemical cues from damage caused by predation (Brown and Laland 2001). Fortunately, an innate predator recognition has been documented in hatchery salmon, but fright responses were muted in substantially different environments (Berejikian et al. 2003). Also, most hatchery salmon are reared on pellet food instead of the live food that they would encounter in the stream. Laboratory experiments have shown that the fish are capable of transitioning from pellets to live food, but not all fish are successful at changing (Brown and Laland 2001). Even if the hatchery salmon grow accustomed to live prey, there is evidence of different consumption patterns, with hatchery salmon eating fewer energy-rich terrestrial insects than wild salmon (Davis et al. 2018). Prey abundance and access varies wildly outside of the hatchery, so it stands to reason that some fish will struggle to adapt when they enter the wild.

On top of naïve behavior, predators may prefer hatchery salmon due to their size. Hatchery salmon tend to be released at larger sizes with limited variation (Nelson et al. 2019). The sizes of hatchery Chinook have a greater overlap with the size preferred by predators than natural-origin Chinook (Nelson et al. 2019). Seals in the Salish Sea have been found to be selective of salmon size, choosing to hunt larger fish rather than smaller, more abundant fish (Nelson et al. 2019). In contrast, aquatic predators may be selective pressures against smaller fish (Duncan and Beaudreau 2019). Additionally, the release protocols for hatchery salmon leave them vulnerable to opportunistic predators as they migrate. Many predatory birds and fish are capable of learned behavior, meaning that they may be able to take advantage of hatchery releases as the timings become more predictable (Nelson et al. 2019, Beamish et al. 1992, Collis et al. 1995). If the end goal of the hatchery is to increase salmon numbers, it is counter-productive to have hatchery salmon outcompete wild salmon in the freshwater only to incur increased mortality soon after entering the ocean.

There is also the matter of disease in hatcheries and possible transmission after release. The circumstances of hatcheries (densely-populated and stressful) are optimal for spreading pathogens in a population of fish. For example, infectious haematopoietic necrosis (IHN) is a major disease in salmon aquaculture that causes sudden mortalities and can be transmitted horizontally and vertically (from individual to individual and from parent to offspring) (Dhar et al. 2016). Contaminated eggs have contributed to the spread of the virus on a global scale. In terms of other diseases, a common link in observed outbreaks is the exposure of facility fish to a water supply that contains infected adults, resulting in rapid infection and high mortality (Amos and Thomas 2002). When wild salmon are exposed to infected hatchery fish, some studies have been unable to identify pathogens in the tissues of the wild fish (LaPatra et al. 2001, Foote et al. 2000). In the Klamath River, juvenile salmon are suffering from high densities of parasites, specifically *Ceratonova shasta*. Juveniles from the hatchery may be exacerbating the effects of the disease, evidenced by an associative relationship between prevalence of infection in juveniles followed by a higher density of spores in the subsequent seasons (Robinson et al. 2020). Once again, the wild salmon in the study appear unrelated to the number of spores (Robinson et al. 2020). Other findings indicate that hatchery smolts do not carry higher burdens of infectious agents than wild fish (Nekouei et al. 2019). Although it is debatable that hatchery salmon pose a transmission risk to wild salmon, it seems that hatchery salmon are particularly impacted, likely due to the higher degree of stress that they experience. In that case, the hatchery is producing fish in poorer condition, reducing the effect of hatchery supplementation.

Section 3 – Is There Hope for Hatcheries?

Despite the drawbacks of salmon hatcheries, there are still some benefits that can be gained. These institutions have been around for a long time and are ingrained within their communities. As the previous section discussed, certain styles of salmon management can lead to unforeseen consequences. However, if there are flaws in the management, it stands to reason that they can be changed to suit the needs of creating sustainable salmon populations. On top of potential reforms, hatcheries often provide a center for learning and community work. Young people can go to hatcheries and learn more about the issues faced by salmon which can lead them to seek out opportunities to help. While hatcheries are certainly not a technological panacea to the salmon problem, they have been able to provide some assistance and that should be acknowledged as choices are made for their future.

3.1. Hatchery Reforms

The term “reform” is rather loose and can be applied to a wide variety of circumstances. For example, hatcheries will have plans in place for reducing genetic effects, improving rearing strategies and release strategies, and disease mitigation. All of these plans are subject to potential refinement as understanding improves. Reform has been happening over the decades, since the conception of hatcheries, as situations have changed and understanding of salmon has improved. Since the early 2000s, reforms have largely been the work of the Hatchery Scientific Review Group (HSRG), and mostly focus on reducing genetic risk to natural populations (Anderson et al. 2020). The HSRG is a scientific panel formed and funded by Congress and made up of scientists from the Washington Department of Fish and Wildlife, the National Oceanic and Atmospheric Administration, the Northwest Indian Fisheries Commission, the United States Fish and Wildlife Service, and individuals nominated by the American Fisheries Society (HSRG 2004). Through this collaborative effort, hatcheries have certainly adapted over the years but, as always, there is still room for improvement.

Hatcheries cannot replace lost habitat or the biodiversity that relies on it, but they can be useful as tools in a much more comprehensive strategy. There are three vital principles that guide recommendations for hatchery reform. Firstly, there must be clear, quantifiable harvest and conservation goals for natural and hatchery populations (HSRG 2014). Next, hatcheries must be designed and run in a manner that is scientifically defensible (HSRG 2014). Lastly, the programs must be monitored, evaluated, and adapted to meet the needs of an inherently dynamic ecosystem (HSRG 2014). Today, hatchery management and genetic plans are submitted to the National Oceanic and Atmospheric Administration by the state governments to describe conservation strategies in detail (WDFW 2023). These plans and actions, along with environmental policy documents and regulations associated with the Endangered Species Acts, are also available for public review (NOAA 2023). Specific guidelines for policy design and implementation are an improvement because it means that hatcheries can be reformed to meet conservation needs more effectively.

There are a number of institutionalized reforms to hatcheries, some of which were recommended by the HSRG and others that were simply an evolution of hatchery practice with the passing of time (Anderson et al. 2020). The idea of broodstock management as a method of maintaining adaptive genetic diversity has persisted through the decades supported by a number of research papers (Reisenbichler and McIntyre 1977, Ryman and Laikre 1991, Swanson et al. 2007). The specific steps of this management may differ depending on if the program is integrated or segregated (a single mixed population or two separated populations). However, the end goal is the same: a diverse and sustained population in a restored and protected habitat. In addition to this, the strategies surrounding rearing and release have changed with time. Rearing strategies refer to the methods of raising fish and include everything from incubation temperature to population density. For example, conservation hatcheries are advised to maintain low rearing densities to improve survival rates (Flagg et al. 1999). Release strategies involve the location, timing, and volume of the fish released which, as touched upon in the previous section, can have profound effects on the salmon. For example, the full-term smoltification process is vital to increasing numbers of returning salmon and benefits from thorough assessment to ensure that the salmon are truly ready (Johnson et al. 2020). Lastly, and most importantly, is monitoring and modification. The Washington Department of Fish and Wildlife, along with tribal co-managers and project partners, have a vast infrastructure in place to monitor key demographic metrics (WDFW 2023, NOAA 2023). This includes mass marking, such as the clipping of adipose fins, in order to quickly identify hatchery-origin salmon.

Although there are official avenues for change and many people continuously monitoring hatchery programs, there are still other recommendations that do not come from the HSRG. Nearly every piece of scientific literature will have suggestions for the future based on the data collected. After all, science must inform policy. Several of the studies referenced in this paper have their own advice for the future, some of which are summarized as follows.

Hatchery salmon experience selection through hatchery practices that can alter their genetics and behavior (Fleming and Gross 1989). Salmon are finely adapted to the environment that they live in but selection for earlier or later migration patterns can introduce a behavior into the population that is contrary to the circumstances of the ecosystem (Brannon et al. 2004). Awareness of this throughout the breeding program can help to mitigate the effects if managers choose to prioritize diversity over performance (Busack and Currens 1995). In addition to monitoring selective pressures, the rearing environment would also benefit from a redesign. There are significant advantages in simulating wild-type habitats for juvenile salmon. Engineered streams can have similar predation levels (i.e. predation by birds or larger fish) and encourage wild-type behavior in juvenile salmon while having a higher survival rate than natural streams (Brannon et al. 2004). Restoration of rivers and streams can also provide massive benefits for young salmon.

The rearing environment is not the only aspect of hatcheries that can be made to emulate the environmental template. Rearing and release strategies can have unintended effects on salmon behavior, such as premature spawning or lingering closer to freshwater instead of migrating out to the ocean. A greater understanding of the interaction between rearing, release, and life history can be very useful in management decisions (Chamberlin et al. 2011). Currently, the hatchery-reared fish are also kept within a specific size range that is very attractive to predators (Nelson et al. 2019). Studies have made hatchery officials more aware of how predators take advantages of hatchery releases. Hatchery releases could be staggered over several months to improve balance in the marine food web with diversification (Nelson et al. 2019). Maintaining diversity in size-at-release can also offer stability to the wider ecosystem to help reduce size-selective mortality (Claiborne et al. 2011). And, of course, if actions are taken to increase diversity of release timing and salmon size, continued monitoring is necessary to document how these adjustments impact the food web.

Another suggestion to further prepare juvenile hatchery salmon is to implement social learning methods. The idea of training fish prior to release may sound unconventional but has been studied as a possible method of reducing behavioral effects from the hatchery (Suboski and Templeton

1989, Hirvonen et al. 2003), although the effectiveness is up for debate (Berejikian et al. 2001). This training would be geared toward improving foraging skills and anti-predator behavior. For example, many social learning experiments begin with a wild-type founder population that is gradually replaced with untrained individuals (Brown and Laland 2001). Introduction of a predator, possibly behind glass or a partition, can trigger the appropriate avoidance responses (Brown and Laland 2001). If the targeted behavior remains in the population after all of the original founders have been removed, then the behavior has been successfully learned. Pre-release training has been successfully used in hatcheries for Atlantic salmon to improve their foraging behavior (Brown and Laland 2002). In order to ensure that the salmon are prepared, the predators and food used in the training should be representative of what they may encounter in the future. The exact training protocols may depend on the species or population, but most salmonids appear to respond favorably to some extent.

To conclude, hatcheries are tools that can be adapted as necessary to meet the needs of conservation or harvest numbers. There is no single answer to how hatcheries should be changed that would solve every conceivable problem. It is likely that salmon – both released and wild – would benefit from a variety of rearing techniques, management strategies, and habitat improvements. As long as research continues and policy remains attentive to that research, hatcheries can become part of the answer to the salmon problem.

3.2. Centers of Learning

Salmon hatcheries also provide an indirect benefit for salmon by being important places for data collection and community learning. Government policy has to be scientifically defensible, and hatcheries produce plenty of valuable data. The numerical records of seasonal water temperature or spawning counts are worth monitoring and, since independent research is often restrained by funding, having hatcheries as a place to consistently collect that data is helpful. In addition to being potential aids to scientific development, some hatcheries are open to visitors and provide opportunities for members of the public to learn about the salmon life cycle. They may run day camps or hatchery tours which encourage the next generation of young minds to care about their local wildlife.

Firstly, there is a wide range of employees associated with hatcheries, from fish culturists to support biologists to research scientists. Whether they interact with the fish on a daily basis or they interpret the data from a distance, all of these people are important for the hatchery system and each carries a particular form of knowledge that may be unique to them. For example, fish culturists bear a lot of practical knowledge that comes from rearing fish for many years (Boyer et al. 2003). Support biologists tend to have a broader knowledge base that is a hybrid of formal science and fish culturing practices (Boyer et al. 2003). Finally, research scientists may be highly specialized, such as studying the retina of coho salmon to determine changes in light absorption over the course of the life cycle (Boyer et al. 2003). This combination of hands-on knowledge and research occurs in hatcheries across the world, handling a variety of fishes (Harrison et al. 2018). However, all of these perspectives come together for the benefit of salmon.

An additional, and very important, perspective is found in tribal groups associated with hatcheries. Traditional ecological knowledge provided by the tribes is separate from scientific knowledge but provides critical information for local dynamics that can be overlooked by modern science (Eijck and Roth 2007). For example, hatchery salmon releases are utilized to reconnect people with salmon and with the environment, as is the case with tribes in the upper Columbia basin. Children release juvenile fish that they raised in the classroom and partake in harvests at historical locations (Baldwin et al. 2022). These fish are also tagged to track survival and behavior which is vital for future monitoring (Baldwin et al. 2022). Given support, hatcheries are unique environments with interesting trajectories for learning even in routine, possibly mundane work (Lee and Roth 2005). The institution is as complex as the salmon are, but with communication, all involved parties can deepen their knowledge.

Scientists are not the only ones who learn from hatchery practices. The U.S. Fish and Wildlife Service has a vested interest in promoting environmental stewardship and they have a variety of broadcasts and in-person nature programs geared toward this purpose (USFWS 2022). Participants gain environmental knowledge that they link to an increased sensitivity for wildlife and a greater awareness of how humans impact their surroundings (Theimer and Ernst 2012). They also specify an increased appreciation and sensitivity for salmon and their local rivers, a sentiment that they work to spread in their local community (Theimer and Ernst 2012). A different approach is employed in Europe where voluntary hatcheries for Atlantic salmon are operated by local anglers. These hatcheries are a visible means of environmental stewardship, providing social, psychological, and conservation benefits to people and the river system alike (Harrison et al. 2018). Involving the public in hatchery rearing processes, restoring streambank conditions, and removing debris helps to build this connection (Schaefer 2006). There is more to this education than simply being outdoors. Interactions with wildlife and emphasis on local culture and ecology greatly influence connection to nature and sense of place. Hatcheries are an excellent place to create this connection.

However, it should be noted that not all hatcheries take advantage of educational possibilities. Visitation policies vary wildly between hatcheries, except within those that have statewide policies in place (Barnes and Whelan 2004) Hatchery operations and initiatives are diverse and, although millions of dollars are spent on hatcheries for maintenance, it does not mean that there is money available for visitor resources (Trushenski et al. 2018). It is possible that education is not considered to be a hatchery purpose, hence it is not involved in consideration of visitation policy. Still, many hatcheries display fishponds and encourage visitors to feed the fish (Barnes and Whelan 2004). Locations within the hatchery that are sensitive to visitors, such as incubation chambers, can be closed or have limited access. These locations still provide teaching opportunities, with the right guidance or posted signage, to inform the public. Providing these explanations is a relatively small investment, especially if volunteers are engaged, and will increase public knowledge of resource management (Barnes and Whelan 2004). More informed people become better stewards of fisheries resources.

3.3. Hopeful Stories

It is absolutely true that salmon hatcheries have a long road of improvements ahead if they are going to serve as tools instead of obstacles. That being said, there is still evidence for potential benefits for salmon. If these successful cases are used to inspire change, then it seems likely that hatcheries can be utilized effectively.

One example of a hatchery with potential is the case of the pink salmon in Prince William Sound, Alaska. The Alaskan population of pink salmon is well-managed and returns have soared from roughly 5 million (prior to hatcheries) to over 26 million (Brannon et al. 2004). Examination of hatchery strays has shown that they overlap with the temporal distribution and genetic makeup of natural-origin fish (Brannon et al. 2004). They are also reproducing successfully and streams with high levels of hatchery fish have similar productivity to streams with low levels of hatchery fish (Brannon et al. 2004). However, it is important to note that this success is dependent on continued monitoring and awareness. More recent work suggests that these hatchery-origin pink salmon have reduced reproductive success relative to their wild counterparts (Shedd et al. 2022). Perhaps the hatchery can recreate its earlier success with a better understanding of interactions between wild and hatchery-origin salmon.

Inch Creek Hatchery in Canada is another example that carries some hope for the future. This hatchery rears four populations of coho salmon, including a population from the nearby Norrish Creek. Norrish Creek, unlike Inch Creek, supports a population of naturally-spawning salmon. Genetic markers reveal that fish from Norrish Creek naturally stray into the Inch Creek population which allows significant genetic exchange to occur between the two populations (Devlin et al. 2021). This gene flow from natural-origin fish may help to reduce the impacts of hatchery programs, possibly moderating the effects of domestication (Devlin et al. 2021). The Inch Creek coho salmon also retained high levels of heritability for size and reproductive traits throughout the study, implying potential for future adaptations (Devlin et al. 2021). To build on this, there is some evidence that hatchery-origin fish do not reduce productivity of natural fish as much as environmental conditions might (Courter et al. 2022). It may be possible that hatchery salmon and wild salmon can coexist without harming each other.

Selection of spawning adults in the hatchery have already been discussed as a potential avenue for concern. One study, which attempted to capture the strength of selection in hatchery and natural environments, found selection operated similarly in both circumstances (Ford et al. 2008). For example, both circumstances selected for larger size in males at approximately the same strength (Ford et al. 2008). The natural environment and the hatchery environment also showed similar selection for later return migration times (Ford et al. 2008). Of course, similar selection strength does not mean that selective mechanisms are the same but understanding selection can possibly allow manipulation of it. Interviews with hatchery staff highlight an awareness of wild phenotypes in salmon and an intention to produce salmon that are as genetically wild as possible (Berseth 2022). There appeared to be genuine interest in the idea of “rewilding” salmon through selective breeding. Selective breeding is likely a controversial application of human technology to the environment, but nearly half of the respondents support selective breeding as a method to fix past mistakes (Berseth 2022). Methods to produce hatchery fish that are similar to wild fish have been successful in some cases. Wild fish surrogates can have similar body symmetry to wild fish and display characteristics or behaviors that are not significantly different from wild fish (Cogliati et al. 2022). The tactics involved include varying strategies in diet, feeding, and tank complexity which can be expanded upon and applied to several hatcheries (Cogliati et al. 2022). Mitigation of domestic selection is a priority, but selection guided by wild characteristics may have potential for future conservation.

Realistically, most hatcheries are employed for the purpose of producing fish for recreational and commercial fishing. However, if the intention is to conserve the population, methods change. For example, the hatchery for coho salmon in California's Russian River is a conservation hatchery with a robust field monitoring program and advanced genetic analysis to preserve the diversity of the brood stock (Reinstein 2020). Conservation-based hatcheries will be more attentive to creating sustainable populations. Perhaps, if hatcheries adapt to population support instead of fishery support, they can provide more support than they currently do. However, this will not be enough. There are factors that no hatchery, conservation or commercial, can fully fight against.

Section 4 – Beyond Hatcheries

The controversy surrounding hatcheries is complex and difficult to solve. Although there is evidence of the harm caused by hatchery practices, some salmon runs would be nonexistent without the annual releases to bolster the population. Regardless of if hatcheries can be reformed for good or if they are wholly bad, they are not the only factor to consider in salmon recovery. All salmon, hatchery origin or not, are subjected to the same poor conditions outside of the artificial environment. Therefore, it is important to discuss exactly what salmon are up against to explain why the controlled environment of the hatchery may be necessary.

4.1 Climate Change

Climate change has countless impacts on the global ecosystem and, it seems as though more are being identified every day. However, some effects are certain, such as increased temperatures in streams and oceans. Although salmon have plastic life histories and are capable of localized adaptation (Crozier et al. 2008, Venney et al. 2021, Lichatowich 1999), they may be unable to survive warmer waters (Munoz et al. 2015). Evidence shows that Chinook salmon have the capacity to increase their thermal tolerance, but they are restrained by their heart which begins to malfunction at around 24.5° Celsius (Munoz et al. 2015). Higher temperatures raise the standard metabolism, the rate of energy use for salmon when they are at rest. This leaves less energy available for activity, meaning that the salmon must rest more, sacrificing feeding (growth) and swimming (predator avoidance).

Climate change has put salmon habitat at risk. Washington has a number of snowmelt-driven river basins and hydrologic simulations have predicted a complete loss of these basins by the 2080s (Mantua et al. 2010). Increased temperatures and lower summer flows will result in a drastic reduction of available habitat for spawning and juvenile salmon (Mantua et al. 2010). Warmer winters are also likely to increase rate of development and, consequentially, lead to earlier emergence, but that does not mean food will be available for the resulting fry (Crozier et al. 2008). It is also likely that higher temperatures will be detrimental for other ecosystems that are vital for young salmon, such as tidal marshes. Increasing ocean temperatures in shallow estuaries may be survivable for smolts, but not for their prey which severely decreases the quality of available habitat (Davis et al. 2022). The severe changes in the natural environment may encourage the use of artificially controlled settings to ensure that salmon survive through the early life stages.

Salmon may find a refuge in hatcheries, where the environment can be controlled, but even that is not certain. The results of a temperature-driven growth model find that warmer temperatures may accelerate juvenile growth in the summer, but also coincide with lower water availability which may increase physiological stress on the fish (Hanson and Peterson 2014). The model predicts that water temperatures at the hatchery being studied (Winthrop National Fish Hatchery) will stay within a tolerable range, but exposure to suboptimal temperatures and stress from heat wave events may increase mortality rates (Hanson and Peterson 2014). To combat this, hatcheries may have to invest in chilling technology or utilize other water sources (such as groundwater) to keep the environment within a tolerable range for rearing salmon. Neither of these are sustainable solutions in the long-term. In addition, artificial selection from hatcheries may exacerbate the effects of climate change. For example, as spawning times have moved earlier through intentional and unintentional manipulation from hatcheries, some runs have seen a decrease in productivity that may be explained by spawning during warmer, unsuitable, conditions (Tillotson et al. 2019). Also, warmer waters weaken immune responses to diseases that are prevalent in hatcheries (Barnett et al. 2020). Despite all of this, climate change is having variable impacts on each salmon species. Coho and Chinook salmon are very negatively affected, but analyses have indicated positive climate-related shifts in abundance of pink and chum salmon (Irvine and Fukuwaka 2011). Hatcheries have the potential to be a controlled environment, insulated from changing global conditions, but the salmon must eventually be released and may not survive what awaits them.

Climate change also affects salmon in ways other than warmer waters. For example, extreme rainfall events and higher flood risks are expected in the coming decades (Hettiarachchi et al. 2018, Cameron et al. 2000). High flow conditions, such as those after a storm, will negatively impact the survival of eggs, fry, and smolts of all salmon that happen to be in the streams (Mantua et al. 2010). Drastic changes in streamflow conditions have been recorded over the last 100 years in the Columbia River basin. Declines in summer flow reduce the amount of available habitat for young salmon which could have a number of impacts, such as longer returning migration times or unusual timing in the availability of food sources (Dittmer 2013). Extreme flood conditions have increased in this basin as well, presenting a challenge for salmon egg nests which may be scoured away and destroyed (Dittmer 2013). However, it is also worth noting that these conditions can be helpful by removing silt from the area which, if left unchecked, could suffocate salmon eggs. That being said, flow variability is increasing in several rivers throughout the Pacific Northwest and is modelled to have a severely negative impact on salmon populations (Ward et al. 2015). Unfortunately, as the frequency of heavy storm events are increasing, the floods may do more harm than good.

There are a number of other indirect impacts from climate change that are difficult to quantify and are, arguably, caused by several factors working together. For example, rising temperatures cause thermal expansion in the ocean which is one of the biggest reasons for rising sea levels (Church et al. 1991). Increased concentrations of carbon dioxide in the atmosphere are taken in by the ocean, raising the acidity to intolerable levels for marine life (Doney et al. 2009). It is easy to point at climate change as the biggest villain in the picture. Unfortunately, climate change has a number of effects other than temperature changes and those effects can be magnified as habitat degrades.

4.2 Habitat Degradation

Salmon require a variety of habitats to complete their life cycle safely. Their migration requires freshwater and saltwater, but the quality of those habitats is also important. The streams must be complex, harboring fast and slow water to suit the feeding and resting needs of the fish. Nearshore brackish habitats are vital to smolts as they adjust to saltwater. Many of these habitats have been lost through urbanization and agricultural development or are declining in quality with negative results to the fish residing in them.

Loss of riparian vegetation in forested watersheds has disastrous results for salmon in freshwater. A number of past papers have examined the impacts of removing vegetation from rivers and, unsurprisingly, the impacts are bad for fish (Harr et al. 1975, Cederholm et al. 1980, Hartman and Scrivener 1993, Kreutzweiser and Capell 2001, Moore and Wondzell 2005). For example, removal of riparian trees correlates with higher stream temperatures while unharvested basins run cooler and experience fewer fluctuations (Pollock et al. 2009). The threat of increased temperatures has already been discussed, and tree loss in riparian areas may exacerbate the effects of climate change. Interestingly, in the study conducted by Pollock et al., shade is unconnected to higher temperatures but it is possible that debris flows, exacerbated by tree loss, are responsible for this (2009). These debris flows can sweep away large woody debris (essential cover for young salmon), or fill rivers with fine sediment. Fine sediment is well-documented as a threat to the survival of salmon eggs and fry as they can prevent oxygenated water flow by filling space between gravel and pebbles (Jensen et al. 2009). Over the past 40 years, watershed logging has intensified and become heavily associated with massive declines in freshwater productivity, including multiple salmon species (Wilson et al. 2022). The removal of woody vegetation causes massive increases in nitrate concentrations and suspended solids, lowering water quality and signifying the importance of vegetation filtration (Larson et al. 2019). To further drive home the importance of riparian forests, an interesting study in Alaska attempted to quantify the monetary value of national forests to the commercial salmon fishery. From 2007 to 2016, the Tongass and Chugach national forests contributed an average of 48 million salmon annually which amounted to about $88 million (Johnson et al. 2019). The fish that originated from these healthy forest tracts represented a significant percentage of Alaska’s commercial salmon fishery, prompting an important discussion about forests in salmon sustenance and recovery. The importance of stable riparian ecosystems (suitable vegetation and maintenance of trees) cannot be overstated.

Beyond forested rivers, but just before entering the ocean, lie estuaries that are crucial habitat for migrating salmon. Estuaries are coastal bodies of brackish water, where salmon can adjust from freshwater to saltwater living before fully entering the ocean. The amount of time that salmon spend in estuaries varies between species with Chinook salmon being the most dependent (Chalifour et al. 2019). For example, in highly impacted estuaries, the survival of Chinook salmon dropped to an average of 0.50% while pristine estuaries boasted an average survival of 1.77% (Magnusson and Hillborn 2003). Loss of habitat can also have indirect effects on salmon foraging behavior. In estuaries with greater than 50% loss, juvenile salmon displayed poor foraging performance in comparison to estuaries with less than 50% loss (David et al. 2016). It is possible that habitat loss creates a density-dependent effect that restrains juvenile salmon foraging, thus affecting their growth and possible survival (David et al. 2016). Within estuaries, eelgrass beds are highly significant for salmon and numerous other fish species. They display high fish diversity and connectedness with other habitats, like brackish marshes and sand flats, which are all vital for general conservation goals (Chalifour et al. 2019). The diversity present in eelgrass habitats provides a plethora of prey for juvenile salmon. Chum and Chinook salmon found in eelgrass blades take full advantage of the zooplankton and invertebrates found in the area, marking eelgrass as a critical supportive habitat for growth during early marine life (Kennedy et al. 2018). Unfortunately, rising sea levels and nearshore development puts all of these habitats at risk.

As for the marine portion of salmon life, one of the primary concerns would be ocean acidification. The rise of atmospheric carbon dioxide is most commonly associated with trapping heat and raising the planet's temperature. However, carbon dioxide also dissolves into the ocean and forms carbonic acid, raising the acidity of the ocean (Raven et al. 2005). This is more of a concern for shellfish and juvenile fish who are more susceptible to changes in the environment. However, there is some evidence that acidification creates favorable conditions for fish-killing algal blooms (Haigh et al. 2015). Also, even though mature salmon can escape direct impacts (except at particularly high carbon dioxide concentrations), the decline of sensitive prey animals can have rippling effects through the food web (Haigh et al. 2015). Although not specific to salmon, carbon experiments on fish show long-term negative effects on metabolic functions, growth, and reproduction (Portner et al. 2004). Amongst the short-term effects, carbon dioxide concentrations alter respiration, blood circulation, and nervous system functions throughout the entire life cycle of tested fish (Ishimatsu et al. 2004, Portner et al. 2004). Ocean acidification is a large-scale problem that impacts all marine creatures and it is certain to have adverse effects on salmon, although those effects may be less understood.

Finally, in terms of habitat degradation, many people would immediately think of pollution. Chemical contamination in rivers and estuaries is a common problem for Pacific salmon species, especially with proximity to urban centers. Juvenile Chinook salmon travelling through contaminated estuaries display an overall survival rate that is 45% lower than Chinook salmon travelling through clean estuaries (Meador 2014). Coho salmon in the same situation had no substantial differences, indicating the sensitivity of the Chinook salmon to the estuary habitat (Meador 2014). However, coho are particularly vulnerable to urban runoff. When coho are exposed to urban road runoff, they suffer high rates of mortality whereas chum salmon do not become visibly sick (McIntyre et al. 2018). The frequency of pre-spawn mortality in coho (death before reproduction) is closely tied to stormwater runoff from urban areas and has recently been tied to the presence of tire tread particles (Tian et al. 2020). Lingering contaminants, such as polychlorinated biphenyls (PCBs), are still present in the environment despite regulation and are accumulated in the bodies of high trophic level predators, such as salmon (Missildine et al. 2005). PCBs are known to cause adverse effects in salmon, such as immunosuppression and deformities (Stein et al. 1995). For the most part, contamination comes from sources such as wastewater treatment plants, agriculture, or human activity, but only a fraction of those contaminants and their effects has been investigated thoroughly.

4.3 Anthropogenic Impacts

Humanity has altered the landscape drastically in a number of different ways, from destroying habitat to installing physical barriers. There are lasting impacts to many of these alterations and they can be seen in the continuing decline of salmon populations. Over the years, the state of Washington has come to recognize the damage caused by these actions and has taken steps to reduce the effects. With a better understanding of salmon needs and habitat complexity, management has been slowly improving for the hope of preserving the iconic anadromous fish.

In order to mitigate the negative effects of timber harvesting, buffer areas of untouched vegetation are necessary. Buffered streams are protected from logging debris and suffer little to no excess erosion (Jackson et al. 2001). In contrast, streams with clearcut banks experienced extreme increases in fine sediment, burying streams in organic matter (Jackson et al. 2001). However, recovery of macroinvertebrates in clear-cut streams appears to be complete within a handful of years, suggesting negative impacts could be short-term (Jackson et al. 2007). A more important factor may be the construction of roads. In fact, some evidence has found that road density and agricultural use create a greater impact than logging (Bradford and Irvine 2000). Waste sediment from road construction is delivered directly into streams and, even if vegetation is restored, road surface erosion continues to lower water quality (Akay et al. 2008). However, road construction has improved over the decades. While the aforementioned results are true for some roads, others show minimal increases in turbidity or suspended sediment concentrations (Arismendi et al. 2017). This may be due to usage of materials that are difficult to erode or active redirection of runoff to filtering hillslopes instead of directly into streams. Despite the downsides of timber harvest, there is hope of management that effectively protects the watershed in which salmon live.

Another significant result of human activity is the installation of barriers to fish passage, such as culverts. Culverts are tunnels, typically under roadways, that allow water to flow without impeding traffic. Studies in western Washington have identified several culverts, deemed legally passable, as fish passage barriers (Price et al. 2011). The rate of noncompliance with culverts is statistically significant in predicting barrier status and, with millions of dollars spent annually on barrier restoration projects, failure to correct these errors amounts to a huge waste of money (Price et al. 2011). In an experimental exposure of coho salmon to culverts, the fish are able to pass through if flow is adequate and if there is a sufficiently-sized pool beneath the culvert for leaping (Mueller et al. 2008). Culverts that replicate the natural conditions of flow, width, and substrate exhibit decreased flow velocity which allows for greater salmon passage and, hopefully, greater future recruitment (Davis and Davis 2011). Fortunately, the 2013 Martinez Decision recognizes the hindrance that culvert pose and orders the state of Washington to repair or replace these barriers (Northwest Treaty Tribes 2013). Hopefully, culverts will become a much smaller problem in the future.

A larger, and perhaps more well-known, barrier to salmon passage would be the numerous dams along Washington’s rivers. Dam removal can be a controversial process, owing to the expenses required and the possible benefits lost (hydroelectricity, water reservoirs, etc.), but dams still represent a significant barriers for salmon (Blumm et al. 2012). A comparison of smolt survival in river systems with and without dams finds that dammed rivers have a survival rate as high or higher than rivers without dams (Welch et al. 2008). There is also an argument to be made that evolutionary selection favors salmon that can survive the current state of rivers with multiple dams and removing them would harm the fish by forcing them to adapt again (Waples et al. 2007). However, multiple studies find evidence of delayed mortality, suggesting that juvenile salmon passing through turbines are weakened in a way that leaves them vulnerable after passing the dam (Ferguson et al. 2006, Arkoosh et al. 2006). And, regardless of survival rates, dams completely block habitat that may otherwise be suitable for salmon. A given section of river has a limited capacity to support a population of salmon, so a restriction on habitat is a restriction on the population.

Dam removal is becoming an increasingly popular method of habitat restoration. The Elwha River dams, removed in 2011, had blocked salmonid migration between the upper and lower reaches of the river for decades. Prior to their removal, supporters hoped that reopening the upper habitat would allow for salmon populations to rapidly recolonize the area and create persistent, self-sustaining populations (Pess et al. 2008). After the removal, environmental DNA tracking has successfully logged all targeted salmon species in the upstream portion of the Elwha River (Duda et al. 2020). It is important to note that Chinook, coho, and sockeye salmon were found in higher numbers than pink and chum salmon, but the latter species spend relatively less time in freshwater anyway. Also, as an aside, there are other methods of helping salmon pass dams, such as fish ladders or the Whooshh fish transport system (Garavelli et al. 2019). Dams represent complex socioeconomic situations, similar to hatcheries, but it is possible that they can coexist peacefully with salmon.

Many salmon streams run through urban areas where surface runoff carries numerous chemicals from a variety of sources. For example, sediment samples taken throughout Washington and Oregon urban streams tested contained significant concentrations of insecticides (Weston et al. 2011). The insecticides, carried via runoff from nearby residential areas, were toxic to sensitive invertebrates that were common prey for salmon. Across a gradient of urbanization, streams in heavily urbanized areas tend to be warmer and coho salmon in those streams experience increased stress due to lower growth efficiencies (Spanjer et al. 2018). Coho salmon are particularly sensitive to urban runoff and display higher frequencies of pre-spawn mortality with higher degrees of urbanization (McIntyre et al. 2018, French et al. 2022). Mortality rates from urban runoff are intermediate in steelhead and Chinook salmon, exemplifying the varying sensitivities between salmon species and the need for more research to prevent risking threatened species (French et al. 2022). Salmon sampled from Puget Sound and the Lower Columbia River estuary contained significant concentrations of polybrominated diphenyl ethers (Sloan et al. 2010). These ethers are of high concern due to the sublethal effects they cause in fish and the accumulation of toxins in fish intended for consumption. Protecting urban watersheds can be very difficult because nutrient input from households and vehicle emissions is, to a certain extent, unavoidable. One suggestion is adopting an ecosystem-based approach, one that focuses on prevention of degradation and restoration of damaged areas at a large scale (Fresh and Lucchetti 2022). Although, this may require widespread change in household usage of chemicals.

In addition to urban areas, agricultural lands and livestock grazing areas pose a certain risk to salmon. Expansion of agricultural lands requires removal of riparian buffers. In cases where these buffers are not maintained, streams experience a substantially negative impact on sediment loads, embeddedness, and large woody debris (DeBano et al. 2016). Essentially, replacing forests with farmland lowers the quality of nearby salmon habitat. Cattle grazing on the streambank removes necessary vegetation, increasing erosion and fine sediment input. Exclusion of livestock is an actively employed method to protect streams which achieves significant improvements in bank stability and canopy density (O'Neal et al. 2016). Unfortunately, success in this method is heavily dependent on monitoring to ensure that fences remain secure, and cattle are kept away from the stream (O'Neal et al. 2016, Krall et al. 2021). Livestock grazing is also strongly associated with increased summer stream temperatures, amplifying the effects of climate change (Kovach et al. 2019). Poorly managed grazing practices can widen channels and reduce water depth, elevating stream temperatures (Kovach et al. 2019). As agriculture is critical to supporting urbanizing populations, the best hope for mitigating this impact would be continued monitoring and accountability of land usage.

4.4 Knowledge Gaps

For all the research being conducted on the state of Pacific salmon, there are still a number of uncertainties. Certainly, human activities can have unforeseen consequences on the ecosystem, and sometimes it can take generations for those consequences to become apparent. Predator responses to environmental conditions are not immediately observable which implies a need to understand the dynamic nature of the planet (Feddern et al. 2023). In addition, organisms respond to their circumstances in different ways. For example, the individual salmon species display different migration patterns that have been slowly changing over time (Quinn and Losee 2022). The number of resident fish in the Salish Sea has been declining and, since the factors affecting residency in salmon are unknown, the decline is not easily explained (Quinn and Losee 2022). A model applied to Klamath River Chinook salmon has recently shown errors that imply the model is no longer unbiased due to unforeseen changes in salmon maturation rates. Overestimates of future abundance have increased in frequency and magnitude, the salmon are maturing earlier, and old data sets are skewing the results because they do not reflect these new maturation rates (Shaftel 2022). Even factors that seem well-recognized, such as the genetic risks detailed earlier in this paper, need further research. Genotypes associated with earlier migration times experience disproportionate risk, so the ability to recognize early-migrating populations and understand their genetics can affect decisions surrounding conservation units (Waples et al. 2022). This highlights the need for research and management to consider the adaptive nature of the ecosystem in attempts to predict outcomes.

The ocean represents a large uncertainty in overall steps to improve salmon survival. It is clear that salmon are sensitive to changes in the ocean, but improved understanding of the underlying biological mechanisms is sorely needed (Beamish 2022). Traditional sampling of salmon during marine phases of their lives is logistically difficult, requiring the usage of innovative technology to improve spatial and temporal coverage (Benoit 2022). As previously discussed, the changing climate is having profound impacts on the ocean's stability. There is limited knowledge of effects on prey quality in these changing conditions, but tests on juvenile salmon indicate the importance of food quality in fish responses (Garzke et al. 2022). In general, the planet is a massive, complicated system with countless organisms and conditions influencing each other in every direction. Information regarding trophic relationships and habitat requirements is lacking in large rivers, suggesting a need to understand common factors across a number of water bodies (Counihan et al. 2022). Identifying impacts on large scales requires collaboration across numerous countries.

The environment is constantly changing, responses are constantly changing, and it can seem impossible to keep up. That being said, work is still being done to understand exactly what is happening to salmon populations and how humanity can help. From the information that is known, plans can be designed and implemented. With monitoring and awareness, plans can be changed to suit future needs.

Conclusion

It is apparent that salmon play a vital role as they are today. Their importance in the lives of the tribes that harvest them is undeniable. The long-standing history that some tribes have with their local salmon runs is built on millennia of respect and stewardship. The State of Washington bears a legal obligation to the tribes to ensure that salmon runs are maintained. The law recognizes the right of the tribes to fish at their usual grounds as well as take half of the harvestable fish. It is also in the State's best interest to preserve salmon runs as they represent a significant portion of the state's fishing industry. In addition to the needs of people, salmon are a keystone species in the streams that they call home. Countless other animals, from killer whales to grizzly bears, take advantage of the salmon as they migrate. Riparian vegetation benefits from the input of marine-derived nutrients. Even the salmon carcasses that are washed ashore play host to a number of insects which are then food for local songbirds. To this end, hatcheries may seem like a logical conclusion to ensure that there are enough salmon to meet all of the aforementioned needs.

Hatcheries release millions of salmon annually and, more often than not, the salmon sold and consumed are salmon from hatcheries. Unfortunately, more and more research find that hatchery salmon are poor substitutes for their wild counterparts. Management decisions have led to inadvertent change on several levels such as genetic diversity and behavioral issues. Earlier spawning times and later release times have put hatchery-origin salmon at risk of being out of sync with their environment. Domestication through hatchery practices has resulted in poor foraging behavior and inadequate predator avoidance. Reproductive success of hatchery salmon is documented to be lower than that of wild salmon. The larger size of hatchery smolts at release may allow them to outcompete wild salmon in freshwater, but it also increases their attractiveness to predators as they migrate. Disease amongst hatchery salmon, as well as the stresses of the hatchery environment itself, weakens the fish toward adverse environmental conditions. Essentially, hatcheries appear to be producing salmon in relatively poor condition compared to wild salmon.

If hatcheries are producing salmon with low chances at survival, reform is sorely needed if hatcheries are to be a useful part of salmon recovery. For example, monitoring the genetic diversity of brood stock will be instrumental to mitigate inbreeding depression. Hatchery-origin salmon that are similar to wild salmon may stand a better chance of surviving outside of the raceway. Styling hatchery release timing and size-at-release after that of wild salmon may help to reduce the negative impacts seen from large-scale, uniform releases. And, of course, continued monitoring of the successes and failures of hatcheries will be indicative of whether or not they should be maintained or removed. An improved understanding of the mechanisms behind selective pressures may allow manipulation of those pressures to "rewild" fish. Additionally, in hatcheries that maintain gene flow between the hatchery-origin fish and local wild populations (if they are present), there seems to be potential for reducing the effects of domestication. Perhaps, the best way to make hatcheries better is to work on understanding the underlying mechanisms rather than creating fish for the sake of having fish.

Another positive aspect of hatcheries is that they exist as places of learning for local communities. Hatcheries can provide valuable information for visitors, educating them on salmon life histories and the problems that stand in the way of sustainable populations. They are also a reliable place to collect consistent data on salmon. Many hatcheries, those that have been in place for decades, have records stretching back to when the hatchery first opened. That information could be valuable in establishing a timeline of change in a local salmon population. Also, as mentioned previously, hatcheries can be a place where tribal communities educate their children about their cultural history. Programs for children can reinforce their sense of place and their connectedness to nature, fostering a new generation of environmental stewards.

Although hatcheries may be a part of salmon recovery, they will never replace a stable habitat. There are many threats to stable habitat now, from climate change to anthropogenic pollution. Increased temperatures and higher peak flow conditions can weaken adult salmon or wipe out nests. Harvesting of riparian vegetation severely reduces the quality of salmon habitat by lowering bank stability and filtration. The loss of riparian buffers has noticeable detrimental impacts on nearby streams, such as an increase of small particles in the water and a lack of shading. Urban centers correlate with incidents of pre-spawn mortality, indicating substantial chemical input from human activity. In addition to what evidence exists now, there is still more to be investigated, whether it is contaminant-related, disease-related, or something new entirely. With all of this in mind, hatcheries may represent a safe freshwater environment with a lower degree of instability.

It is vital to reiterate that this paper is far from exhaustive. Each concept discussed can very well be a paper of its own to properly capture the ins and outs of what salmon are up against and what hatcheries can do. Also, circumstances change between hatcheries, between salmon populations, and between local industries. The best steps forward probably lie in recognizing these differences and being prepared to evaluate plans and implement changes if necessary. This includes steps like getting rid of hatcheries, removing dams, and large-scale restoration in watersheds. There is a lot to keep in mind other than hatcheries alone, and if they can be reformed to mitigate risks, they may be a safe haven from failing habitats. So, if artificial propagation has a place in the future of salmon recovery, it could probably stand to learn from the salmon itself and adapt to situations as needed.

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